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Heat Transfer Analysis of the LWR Pressure Vessel Steel Irradiation Capsules in the Oak Ridge Research Reactor-Pressure Vessel Benchmark Facility

Ilana I. Siman-Tov

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreement DOE 40-551-75

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UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

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NUREG/CR-2053
ORNL/NUREG/TM-427
Dist. Category R5

Contract No. 7405-eng-26

Engineering Technology Division

HEAT TRANSFER ANALYSIS OF THE LWR PRESSURE VESSEL STEEL IRRADIATION CAPSULES IN THE OAK RIDGE RESEARCH REACTOR-PRESSURE VESSEL BENCHMARK FACILITY

Ilana I. Siman-Tov

Manuscript Completed — March 8, 1982
Date Published - April 1982

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Prepared for the
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NRC FIN No. B0415

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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CONTENTS

Page

FOREWORD v

SUMMARY vii

Argonne National Laboratory vii

Hanford Engineering Development Laboratory vii

Oak Ridge National Laboratory vii

1. ARGONNE NATIONAL LABORATORY 1-1

1.1 Introduction 1-1

1.2 Nondestructive Testing Technology 1-1

1.2.1 NDE Techniques for In-Service Weld Inspection . . 1-1

1.2.1.1 Evaluation of a pulsed eddy-current system for stainless steel weld inspection 1-1

1.2.1.2 Ultrasonic wall-thickness measurement in grooved duplex tubes 1-2

1.3 References 1-6

2. HANFORD ENGINEERING DEVELOPMENT LABORATORY 2-1

2.1 Introduction 2-1

2.2 Ultrasonic Methods and Equipment 2-1

2.3 Developments 2-2

2.3.1 Analysis Procedures 2-2

2.3.2 Data Validation 2-3

2.3.3 Time-Domain Analysis 2-8

2.3.3.1 Peak voltage analysis 2-8

2.3.3.2 Signal enhancement 2-8

2.3.3.3 Correlation 2-13

2.3.4 Frequency-Domain Analysis 2-16

2.3.4.1 Discrete fourier transform 2-20

2.3.4.2 Power density spectrum 2-22

2.3.4.3 Moments 2-27

2.4 References 2-30

3. OAK RIDGE NATIONAL LABORATORY 3-1

3.1 Introduction 3-1

3.2 Developments 3-1

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ACKNOWLEDGMENTS

This work was primarily funded by the NRC under the LWR Pressure Vessel Irradiation Surveillance Dosimetry Program.

The author gratefully acknowledges the contribution of the following people to the understanding and successful completion of this analysis: E. J. Allen for clarification of the nuclear heatup problem and assistance in the implementation of the AMPX code; J. F. Mincey for providing experimental data and analysis of nuclear heating rates in HSST; G. H. Llewellyn for his excellent independent thermal analysis of the final design; and J. A. Conlin for his guidance and support throughout this program.

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Ilana I. Siman-Tov

ABSTRACT

The purpose of this study was to determine a design for irradiation capsules for the Light Water Reactor (LWR) Pressure Vessel Wall Simulation (PVWS) experiment in the Poolside Facility of the Oak Ridge Research Reactor. The experiment's structural configuration is based on the actual configuration of an LWR PV wall, the surveillance specimen capsule, and the thermal shield. The design temperature at which the metallurgical test specimens are to be maintained in the experiment is based on an LWR PV operating temperature of 288°C.

A detailed investigation of the thermal behavior of the proposed design configuration was performed to arrive at an optimum flexibility design that will ensure a uniform temperature distribution of 288°C ± 10°C for all the test specimens, while allowing for uncertainties in thermal behavior, component dependability, and nuclear heating rates in the iron.

The conclusions of these studies determined the final design parameters for these irradiation capsules.

---

1. INTRODUCTION

The advent of nuclear reactors focused the attention of regulating and code-writing bodies on the special problems associated with nuclear pressure vessels (PV). A 1966 survey conducted by the International Atomic Energy Agency (IAEA) with regard to PV codes in member organizations pointed out that these problems are partially due to the PV's very large size, high operating pressure, and storage of large amounts of energy.[1] The main problem, however, is that these PVs operate in a high-radiation field that affects their material properties and activates the material so that routine inspection is not possible.

The special radiation effects of concern include the following:

1. Embrittlement of the PV steel is caused by neutron exposure (Fig. 1).
2. Nuclear activation of the PV material makes periodic routine inspection often impossible.
3. Vessels are designated as containing lethal substance, making containment a major concern.
4. Thermal stresses develop in the PV wall as a result of changing operating conditions and nuclear heating within the wall material.

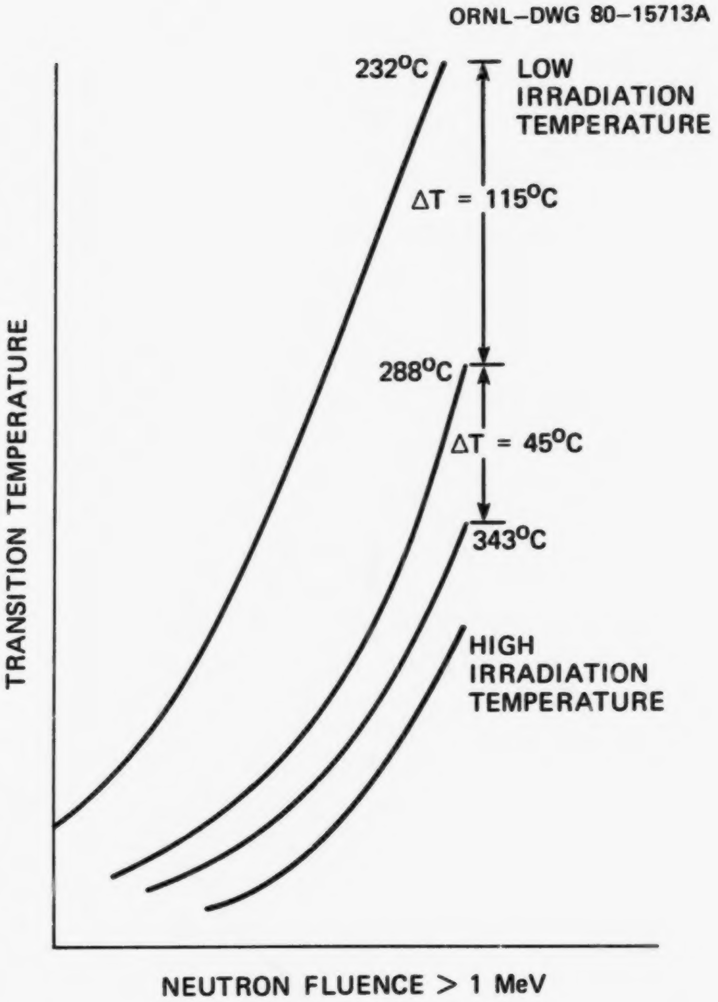

Fig. 1. Trends of transition temperature increase with neutron fluence at various irradiation temperatures.

In 1964, a new Sect. III of the ASME code was published entitled "Nuclear Vessels." One requirement of this code is to check the PV material periodically for the combined effects of fabrication, stress, and neutron exposure by means of surveillance specimens irradiated in the reactor. Since 1964, an effort has been continuously under way to develop new codes and refine regulations that will permit safer yet more economically feasible designs for nuclear PV. Surveillance programs were applied to the existing reactors, and by 1970 the following guidelines for a good surveillance program were put forth:[2]

1. Steel from the actual PV should be used for irradiation.
2. Irradiation locations and conditions should be chosen that duplicate as closely as possible the physical and nuclear conditions in the vessel. Also, a complete record of the material history should be retained along with segments of actual vessel steel for future reference.
3. The specimens should be made in accordance with pertinent standards.
4. The testing apparatus should be carefully calibrated.
5. The dosimetry and spectral analyses should be done using the best and latest nuclear constants available.

Many experimental and calculational benchmarks related to PV steel in nuclear reactors were developed. The status and future requirements of this program were reviewed in 1977 by the Electric Power Research Institute (EPRI).[3] Recommendations were made for expansion of programs aimed at better definition of neutron flux and spectra and their influence on PV steel properties. Among the areas emphasized were the development of (1) reliable experimental and calculational benchmarks in dosimetry and dosimetry techniques and (2) better correlations of material property changes with changes in neutron spectra.

Currently, a worldwide effort is under way in support of improving, maintaining, and standardizing neutron dosimetry, damage correlation, and the associated reactor analysis procedures used for predicting the integrated effects of neutron exposure on Light Water Reactor (LWR) PV. As part of this effort, the Nuclear Regulatory Commission (NRC) and other participants are sponsoring the LWR PV Irradiation Surveillance Dosimetry Program. The major benefit of this program will be a significant improvement in the accuracy of the assessment of the remaining safe-operating lifetime of LWR PVs.

The particular program sponsored at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, consists of three parts: (1) Neutron Field Characterization -- Transport Methods, (2) Benchmark Fields, and (3) Dosimetry and Damage Correlation Analysis. The Oak Ridge Research Reactor (ORR)[4] was chosen for the PV Wall Benchmark Facility because of its Poolside Experimental Facility (PSF). This PSF consists of a water pool adjacent to a thin aluminum window in the vessel wall of the ORR. Since the ORR is an LWR, the PSF provides neutron flux distribution and spectra similar to those encountered in a power LWR. The planned PV Wall Benchmark Facility is designed to simulate an LWR PV wall, thermal shield, and surveillance specimens configuration (Fig. 2). The two irradiation capsules going into this facility provide the surveillance specimens and the PV wall specimens with a thermal and nuclear environment similar to that encountered in an operating LWR.

2. OBJECTIVES AND DESIGN CRITERIA

The PV Wall Benchmark Facility, with the surveillance specimen and the PV Wall Simulation Capsule, represents the configuration highlighted in the schematic of the LWR PV (Fig. 2). To complete the simulation of an LWR PV, the metallurgical test specimens placed in the capsules must

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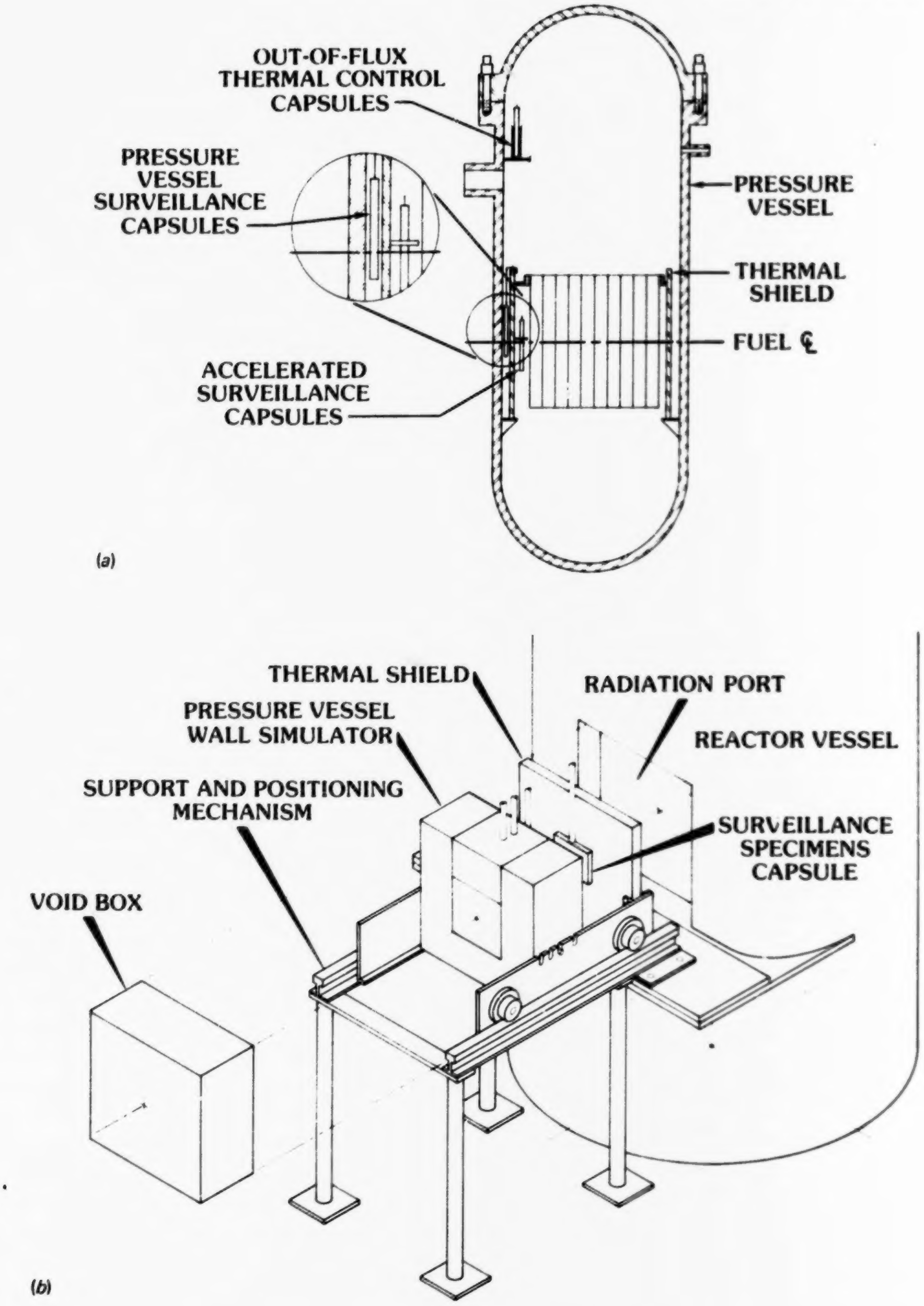
OUT-OF-FLUX
THERMAL CONTROL
CAPSULES
PRESSURE
VESSEL
SURVEILLANCE
CAPSULES
PRESSURE
VESSEL
THERMAL
SHIELD
FUEL ℄
ACCELERATED
SURVEILLANCE
CAPSULES
(a)
THERMAL SHIELD
RADIATION PORT
PRESSURE VESSEL
WALL SIMULATOR
REACTOR VESSEL
SUPPORT AND POSITIONING
MECHANISM
SURVEILLANCE
SPECIMENS
CAPSULE
VOID BOX
(b)

Fig. 2. LWR PV schematic of (a) LWR PV and (b) a proposed experimental simulation in ORR PSF.

be provided with a thermal and nuclear environment similar to that of an operating LWR.

The main objective of the thermal analysis is to determine design parameters that will ensure temperature control at 288°C ± 10°C in all specimen assemblies for the duration of the experiment. Because the capsules exposed to the radiation field in the reactor cannot be modified, the design must provide enough thermal control flexibility to achieve the specified temperature distribution in all the specimens. The thermal control must compensate for (1) the space and time variations in the nuclear heating rates, (2) end losses around the edges of the capsules, and (3) uncertainties caused by physical peculiarities unaccounted for in the computational models.

Because of the high sensitivity of the PV-steel transition temperature increase to neutron fluence and to the irradiation temperature (Fig. 1), it is of primary importance not to deviate from the design temperature by more than the ±10°C allowed. This will ensure that the accumulated fluence effect in the specimens will not be significantly distorted.

The following design criteria are set to accomplish this objective:

1. The temperature in the metallurgical test specimens (Fig. 3) must be kept at 288°C ± 10°C for the duration of the experiment.
2. The configuration of the metallurgical test specimen assemblies and their positions in the capsules are fixed (Fig. 4).
3. The capsule components must be designed to minimize changes in the neutron spectra at the positions of the different specimen assemblies.

A preliminary evaluation of thermal gradients caused by the geometric and material restrictions presented in Fig. 4 indicated that if a temperature of 288°C was maintained at the capsule center, temperature differences >10°C were likely to occur in the specimens. Temperature differences will also result from:

1. nonhomogeneous nuclear heating rates in the steel components caused by the variation in neutron and gamma fluxes over the irradiation region, variation in fluxes during a fuel cycle, and self-shielding effects in the irradiated materials;
2. boundary effects at the edges of the specimen assemblies; and
3. unknown thermal contact resistance between the specimens and between other surfaces in the system.

Consideration of these factors in preliminary calculations indicated that both internal cooling and electric heating would be necessary to provide the desired temperature control in all of the specimens. Heat transfer should be limited as much as possible to the direction that is perpendicular to the specimen assemblies so that heat paths through the specimens will be a maximum of 12.7 mm long.

The proposed flexibility of the thermal control is to be achieved by variable and independent heater regions and variable gas mixtures (from pure helium to pure neon) that act in conjunction with the cooling system to maintain the specified temperature distribution for the experiment.

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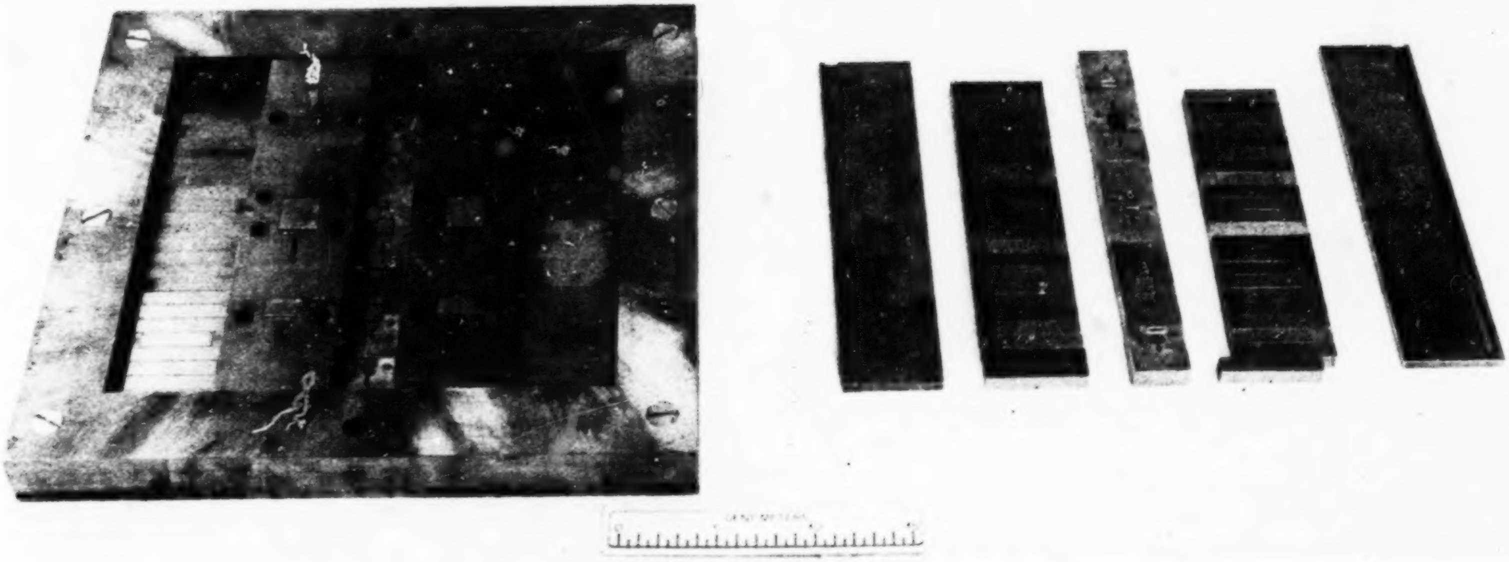

Fig. 3. Configuration of metallurgical test specimen assembly.

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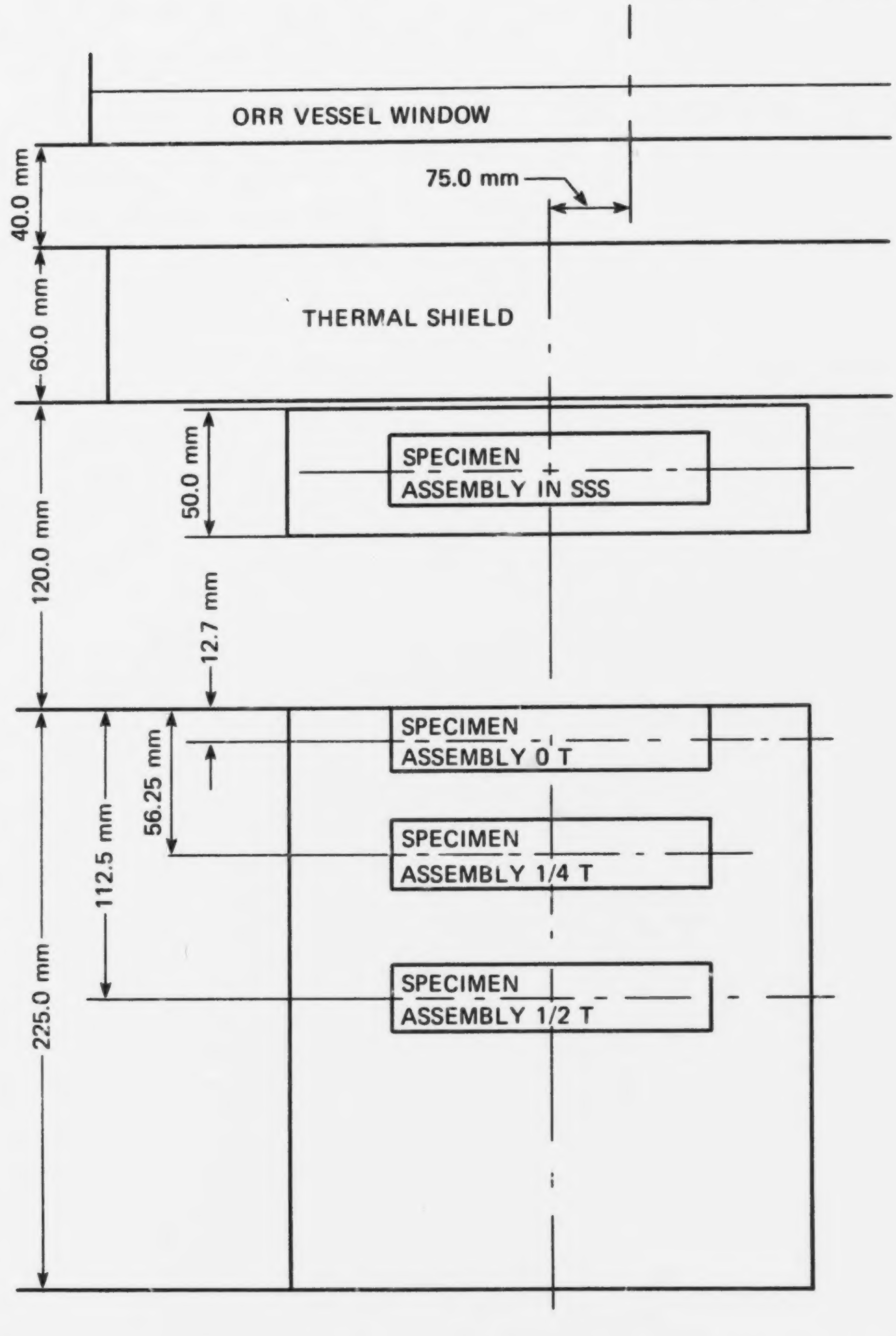
ORR VESSEL WINDOW
40.0 mm
75.0 mm
60.0 mm
THERMAL SHIELD
120.0 mm
50.0 mm
SPECIMEN
ASSEMBLY IN SSS
12.7 mm
225.0 mm
112.5 mm
56.25 mm
SPECIMEN
ASSEMBLY 0 T
SPECIMEN
ASSEMBLY 1/4 T
SPECIMEN
ASSEMBLY 1/2 T

Fig. 4. Spatial arrangement of the specimen assemblies in the experiment.

2.1 Description of the Proposed SSS Capsule Design

The design specification for the Surveillance Specimen Simulation (SSS) capsule limits its thickness to 50 mm while the contained specimen assembly is 25.4 mm thick. Therefore, an elaborate cooling system for this capsule cannot possibly be provided, even though the nuclear heating rates are expected to be about five times higher than in the Pressure-Vessel Wall Simulation (PVWS) capsule. However, both front and back surfaces can serve as heat sinks for the heat generated in the capsule internals so that the maximum path length within the specimen assembly is only 12.7 mm in the preferred direction.

The proposed design of the SSS capsule consists of a stainless steel container and an internal sandwich arrangement of a heater plate-framed specimen assembly—heater plate combination (Fig. 5). A gas gap is required to maintain the 288°C ± 10°C in the specimens relative to the pool water temperature of 38°C. Better insulation, combined with a much smaller heat transfer area in the other two directions, should force most of the heat to exit through the front and back surfaces.

The main objectives in modeling the thermal behavior of the SSS capsule are to determine the sizes of the front and back gas gaps that will

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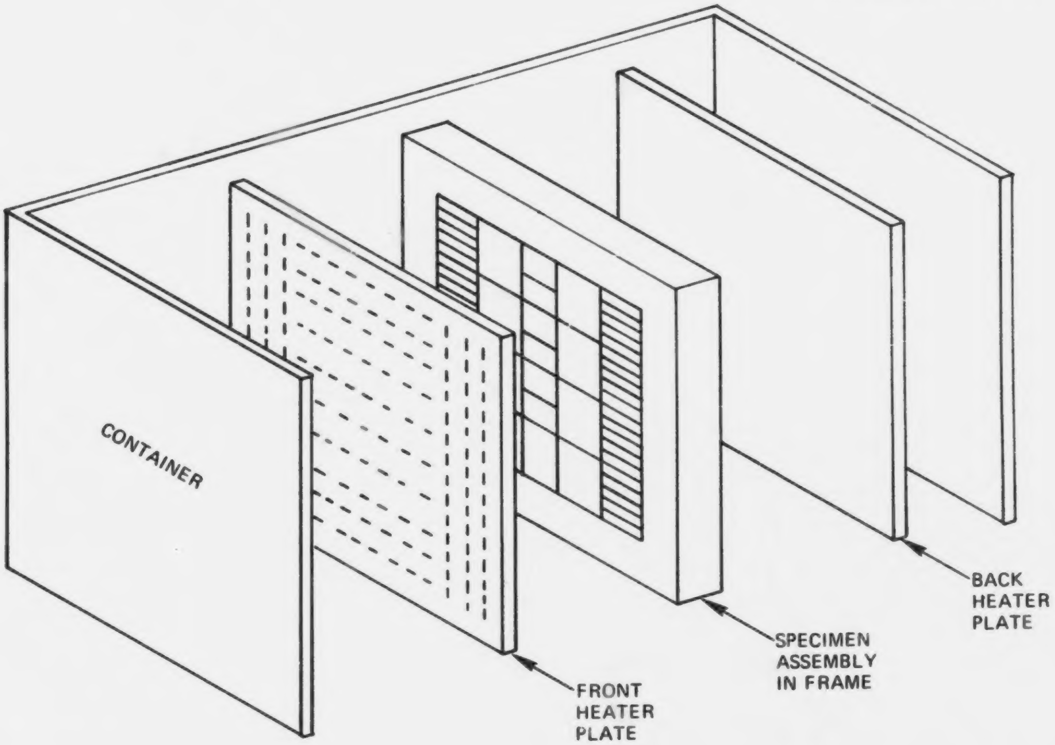

Fig. 5. Exploded view of proposed SSS capsule design.

maintain the design temperature in the specimens, while allowing the heaters to provide enough heat to flatten temperature gradients caused by factors mentioned previously.

2.2 Description of the Proposed PVWS Capsule Design

The design specification for the PVWS capsule requires its entire thickness to be 225 mm. The specimen assemblies contain 100 metallurgical test specimens in a 254 × 254 × 25.4 mm array, similar to that shown in Fig. 3. These assemblies are located within the capsule at three positions: (1) the 0-thickness (0-T) position, which is as close to the front face as the design permits; (2) the 1/4-thickness (1/4-T) position, which places the vertical midplane of the assembly parallel to the reactor window at 56.25 mm from the front face; and (3) the 1/2-thickness (1/2-T) position, which places the vertical midplane of the assembly at 112.5 mm from the front face of the capsule. To maintain the simulation of a PV wall, the specimens have to see the same neutron spectrum that the wall sees in an LWR; therefore, most of the capsule material must be steel. To prevent gradients from exceeding the ±10°C, internal cooling is necessary.

The proposed design of the PVWS capsule consists of a stainless steel container, a stack of three sandwiched arrangements of heater plate-specimen assembly-heater plate-cooler plate (Fig. 6). The back of the capsule is made of low-carbon steel filler plates. Gas gaps are required between (1) the front heater plate and the container front face, (2) the cooler plates and the cooler tubes (gas annuli), and (3) the internal assembly and all the other container surfaces. Because the first two types of gaps are in the path to the major heat sinks, they act as a buffer between the desired temperature of 288°C and the water temperature of about 38°C. The other gaps serve as insulation so that most of the heat is forced into the designated heat sinks.

The main objectives in modeling the thermal behavior of the PVWS capsule are to determine (1) the front and annular gas gaps, (2) the necessary water flow to maintain turbulent flow in the tubes (Appendix C), and (3) the heater power needed to maintain the flat temperature in the specimen assemblies under various nuclear heat generation rates in the iron.

3. COMPUTATIONAL HEAT TRANSFER MODELS

The more complex (nonlinear) heat transfer calculations for the capsules were modeled using the HEATING5 conduction code.[5] This code is designed to solve steady-state and/or transient heat conduction problems in one-, two-, and three-dimensional (1-, 2-, and 3-D) Cartesian or cylindrical coordinates or 1-D spherical coordinates. The thermal conductivity, density, and specific heat may be space and temperature dependent. The thermal conductivity may be anisotropic. Materials may undergo a phase change. Heat generation rates may be dependent on time, temperature, and position. The boundary conditions may be (1) surface-to-boundary, (2) surface-to-surface, (3) fixed temperatures, or (4) any combination of prescribed heat flux, forced convection, natural convection, and

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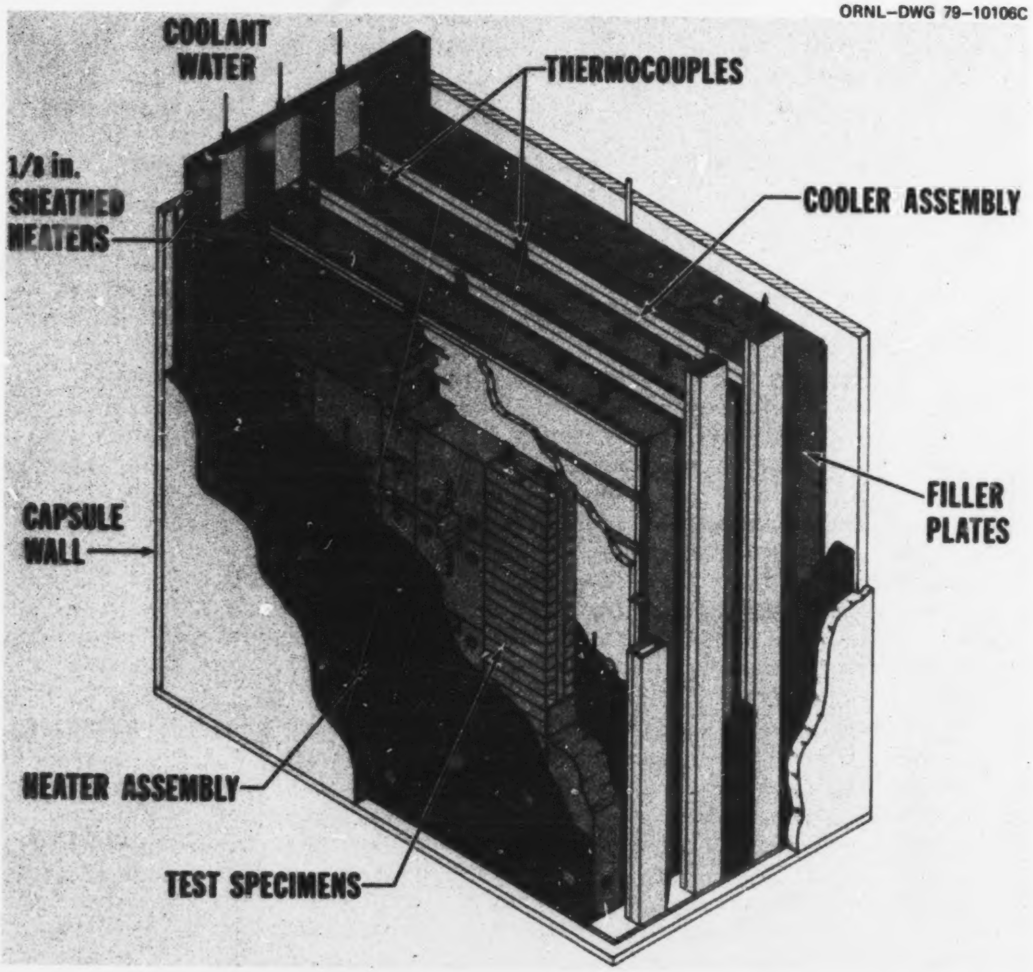
COOLANT WATER
THERMOCOUPLES
1/8 in. SHEATHED HEATERS
COOLER ASSEMBLY
FILLER PLATES
CAPSULE WALL
HEATER ASSEMBLY
TEST SPECIMENS

Fig. 6. Cutaway isometric view of proposed PVWS capsule design.

radiation. The boundary condition parameters may be time and/or temperature dependent. The mesh spacing can be variable along each axis.

The basic form of the steady-state heat balance equation to be solved is

$$\dot{Q}_0 + \sum_{m=1}^{M_0} {}_0K_{\alpha m} \left(T_{\alpha m} - T_0\right) = 0 \ , \qquad (1)$$

where

0 = the node number for which a heat balance is computed,
$\dot{Q}_0$ = space-dependent heat generation rate,
M_0 = total number of neighboring nodes,
${}_0K_{\alpha m}$ = temperature- and space-dependent conductance from node 0 to node m.

A general node configuration in a 2-D XZ geometry is shown in Fig. 7. A nonuniform grid spacing arrangement around node 0 in the direction of all neighboring nodes is presented such that if

$$\Delta X_1 \neq \Delta X_2 \neq \Delta Z_1 \neq \Delta Z_2 ,$$

then

$$\Delta V_1 \neq \Delta V_2 \neq \Delta V_3 \neq \Delta V_4 .$$

Materials, heat generation rates, and boundary conditions may be different in each region, R_j. Therefore ${}_1K_{\alpha m}$ may be different in each component of the node, and the conductance from node 0 to node m may consist

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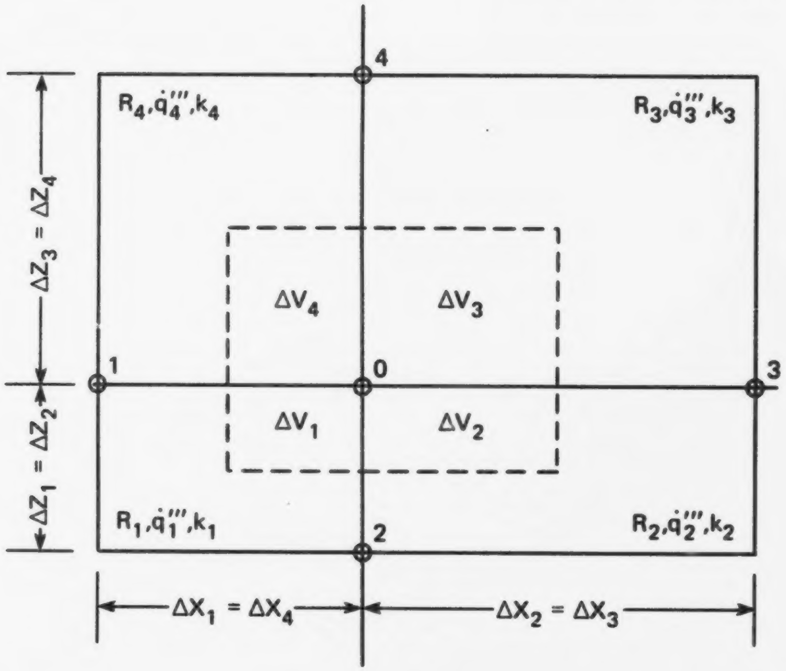
4
$R_4, \dot{q}_4''', k_4$
$R_3, \dot{q}_3''', k_3$
$\Delta Z_3 = \Delta Z_4$
ΔV_4
ΔV_3
1
0
3
ΔV_1
ΔV_2
$\Delta Z_1 = \Delta Z_2$
$R_1, \dot{q}_1''', k_1$
2
$R_2, \dot{q}_2''', k_2$
$\Delta X_1 = \Delta X_4$
$\Delta X_2 = \Delta X_3$

R_i = REGION NUMBER, WHERE i = 1,2,3,4
$\Delta X_i, \Delta Z_i$ = HORIZONTAL AND VERTICAL DISTANCES BETWEEN ADJACENT GRID LINES
ΔV_i = VOLUME COMPONENT FOR NODE 0 IN REGION R_i
$\dot{q}_i'''$ = VOLUMETRIC HEAT GENERATION RATE IN REGION R_i
k_i = CONDUCTIVITY OF MATERIAL IN REGION R_i

Fig. 7. HEATING5 nodal description for two-dimensional XZ geometry.

of two parallel conductances. The volumetric heat generation rate for node 0 may consist of up to four different components in a 2-D problem; for example, if node 0 is at a corner of four different regions each with its own heat generation rate, then

$$\dot{Q}_0 = \sum_j \dot{q}_j''' \Delta V_j \qquad (j = 1, 2, 3, 4) ,$$

where

$\dot{q}_j'''$ = volumetric heat generation rate in part j of the nodal volume,
ΔV_j = component of the volume of node 0 associated with region R_j.

These components are described in Fig. 7. Then, the total heat generation rate computed at node 0 is

$$\dot{Q}_0 = \dot{q}_1''' \frac{\Delta X_1}{2} \frac{\Delta Z_1}{2} + \dot{q}_2''' \frac{\Delta X_2}{2} \frac{\Delta Z_1}{2} + \dot{q}_3''' \frac{\Delta X_2}{2} \frac{\Delta Z_3}{2} + \dot{q}_4''' \frac{\Delta X_1}{2} \frac{\Delta Z_3}{2} ,$$

and all the conductances are

$${}_0K_{\alpha 1} = \frac{k_1}{\Delta X_1} \frac{\Delta Z_1}{2} + \frac{k_4}{\Delta X_1} \frac{\Delta Z_3}{2} ,$$

$${}_0K_{\alpha 2} = \frac{k_2}{\Delta Z_1} \frac{\Delta X_2}{2} + \frac{k_1}{\Delta Z_1} \frac{\Delta X_1}{2} ,$$

$${}_0K_{\alpha 3} = \frac{k_2}{\Delta X_2} \frac{\Delta Z_1}{2} + \frac{k_3}{\Delta X_2} \frac{\Delta Z_3}{2} ,$$

$${}_0K_{\alpha 4} = \frac{k_3}{\Delta Z_3} \frac{\Delta X_2}{2} + \frac{k_4}{\Delta Z_3} \frac{\Delta X_1}{2} .$$

A convection boundary condition may exist at a boundary node in these models so that, for example, node 3 in the figure will have a sink temperature. If region 2 and 3 are assumed to have different boundary conditions, then their contribution will be summed separately as follows:

$$h_2 \frac{\Delta Z_1}{2} (T_{s_3} - T_0) + h_3 \frac{\Delta Z_3}{2} (T_{s_3} - T_0)$$

in Eq. (1).

The steady-state problem is solved by the point successive overrelaxation method using a finite difference formulation. Another technique solving directly for T is available for the 1- and 2-D problem.[6]

This technique was chosen for most of the computational HEATING5 models in this work. For a linear problem, the technique yields a direct solution of AT = B by using either a tridiagonal matrix solver TRIDIG[7] or a banded matrix solver BANSOL.[8] For nonlinear systems of equations, an iteration procedure is set up using one of the above solvers. The convergence criterion is based upon nodal heat residuals.

A steady-state HEATING5 model requires input data in ten blocks of information:

1. overall problem parameters set input-output options, choice of coordinate system, array dimensions, and convergence criteria;
2. region description: region boundaries, material content, volumetric heat generation rate, and initial temperature guess;
3. material description: conductivity, specific heat, and density (constants and/or associated function numbers);
4. heat generation: constant and/or associated function number;
5. initial temperature: constant and/or associated function number;
6. boundary conditions: options (a) surface-to-boundary, (b) specified surface temperature, and (c) surface-to-surface; types (a) forced convection, (b) radiation, (c) natural convection, and (d) specified heat flux;
7. grid description: gross grid line specification in each coordinate direction used in the model (includes at least all region boundaries appearing in the region description);
8. analytic functions previously specified;
9. tabular functions previously specified; and
10. restart temperature distribution if problem is a continuation of a previous run.

Since the material properties, nuclear heating rates in iron, and external boundary conditions will remain the same in all models, they will be presented first in the following sections.

3.1 Material Thermal Properties

The material thermal conductivities used in the heat transfer models are given in Table 1. Intermediate values are obtained by linear interpolation.

3.2 External Boundary Conditions

Experimental data obtained for the heat transer coefficient in the ORR PSF[9] include values into the boiling range at temperatures exceeding 116°C (240°F), which is the saturation temperature of water at the experimental facility (about 9.2 m of water head) (Fig. 8).

Table 1. Temperature-dependent thermal conductivities of materials in SSS and PVWS capsules

Material name	Temperature [°C (°F)]	Conductivity [W/m•°C (Btu h•ft•°F)]
SS304L[a]	0 (32)	13.392 (7.741)
	100 (212)	16.321 (9.434)
	500 (932)	21.762 (12.579)
C-Steel[a]	25 (77)	71.143 (41.123)
	800 (1472)	29.294 (16.933)
Helium[b]	26.7 (80)	0.15105 (0.08731)
	76.7 (170)	0.16605 (0.09598)
	126.7 (260)	0.18407 (0.1064)
	176.7 (350)	0.20106 (0.11622)
	226.7 (440)	0.21807 (0.12605)
	326.7 (620)	0.25007 (0.14455)
	426.7 (800)	0.30408 (0.17577)
Neon[a]	50 (122)	0.05064 (0.02927)
	100 (212)	0.05650 (0.03266)
	200 (392)	0.06612 (0.03822)
	300 (572)	0.07539 (0.04358)
	500 (932)	0.09081 (0.05249)

[a] Data from B. Mazzoli, *A Compilation of Thermal Property Data for Computer Conduction Calculations*, Livermore, California, TID-4500, UC-25 (February 1969).

[b] Data from R. H. Perry and C. H. Chilton, *Chemical Engineers' Handbook*, McGraw-Hill, New York, 1972.

3.3 Nuclear Heating Rate in the Steel Components

The results of the calculated nuclear heating rates in the steel components as a function of the position relative to the face of the thermal shield are presented in Fig. 9.

Because the computed nuclear heating rate is derived from a 1-D cylindrical model (Appendix D), it was modified by a sine function accounting for the variation in the Z-direction of the model. The sine function was used to account for the 1.4 peak-to-average distribution[10] of the nuclear heating rate about the reactor horizontal midplane (Fig. 10).

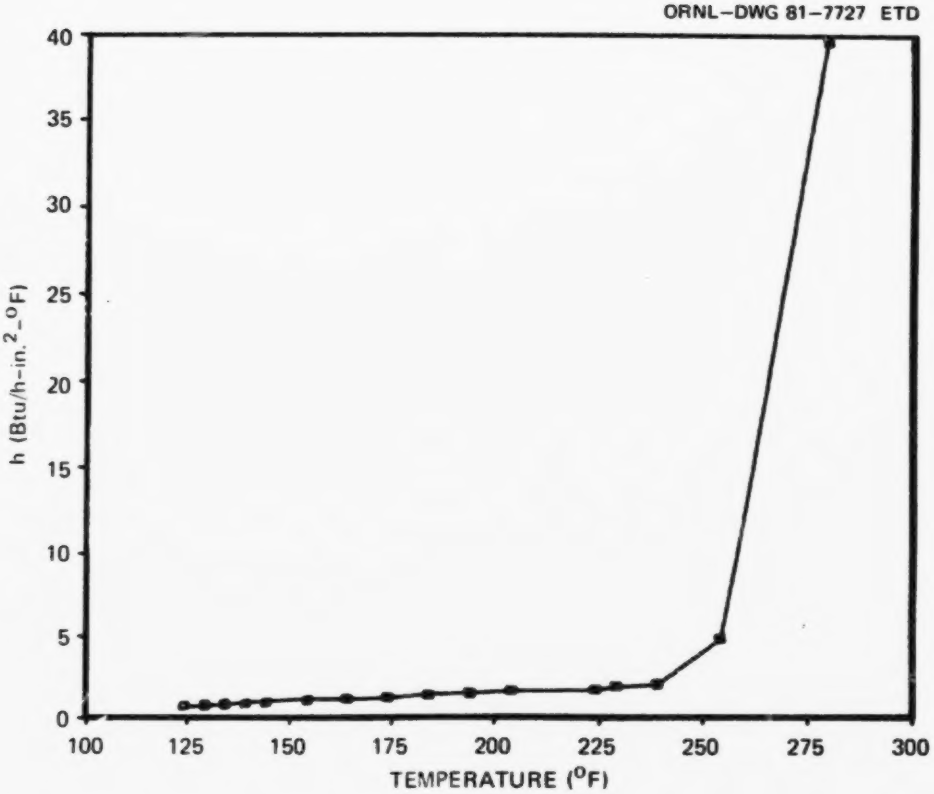

Fig. 8. Temperature-dependent heat transfer coefficient from surfaces immersed in ORR PSF water.

3.4 Computational Model of the SSS Capsule

The purpose of the SSS model is to determine a gas gap size in the direction perpendicular to the reactor window that will allow enough heat to be removed in the event of an underestimated nuclear heating rate in the steel components. This gap size must still allow the heaters to supply enough heat to maintain a flat temperature distribution in the specimens.

A 2-D XZ model was developed for the SSS capsule. A geometric description of the model is shown in Fig. 11, and definition of the regions is given in Table 2.

The following assumptions are made in the basic model:

1. All heat in the capsule internals is transferred by heat conduction only. Because the maximum allowed internal temperature cannot exceed 298°C and the pool water temperature stays between 21 and 40°C, radiation and natural convection in the gas gaps are negligible compared to the total heat loss from the capsule internals (Appendix C). Since a

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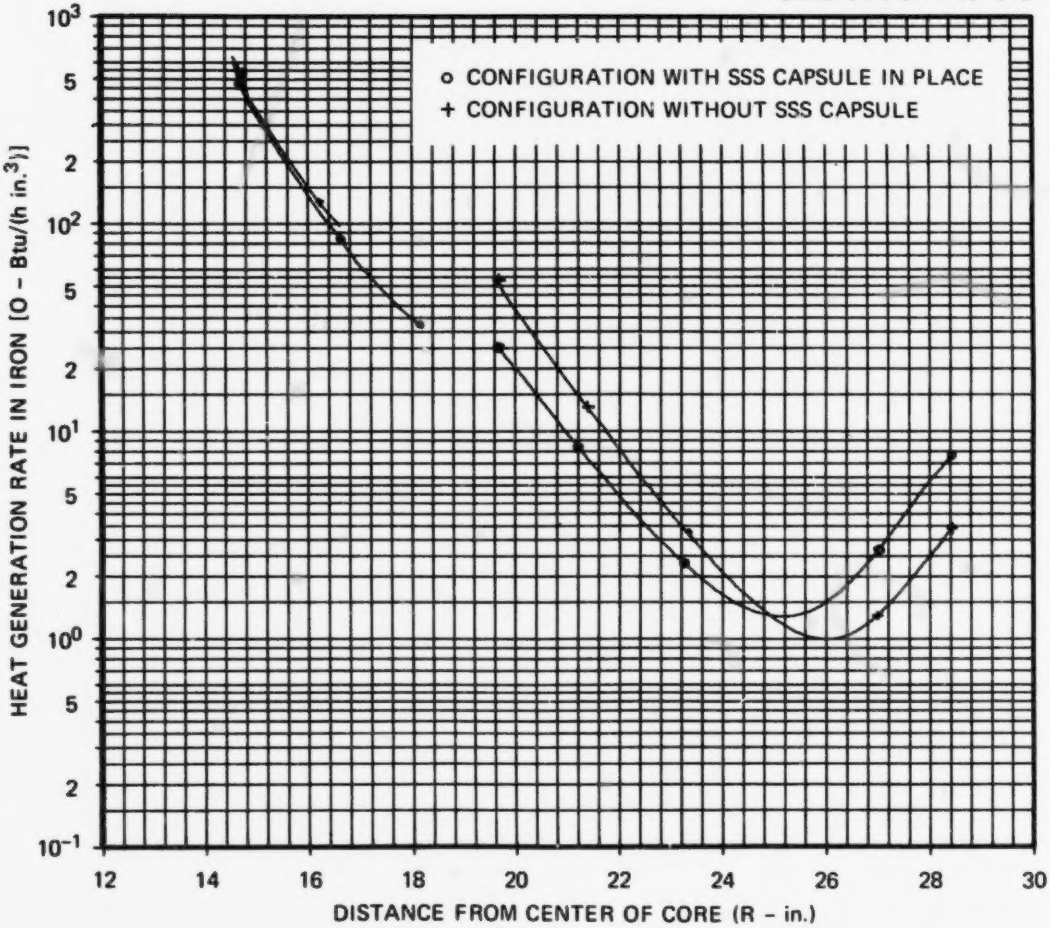

Fig. 9. Nuclear heating rate in PV steel configuration in ORR PSF.

conservative estimate of the gap size will be obtained (in the sense that all the heat has to be transferred by conduction through the gap), radiation and natural convection were not included in the internal regions of the capsule.

2. The specimen assembly was modeled as a solid piece of steel where contact resistance between specimens and other components' interfaces was neglected. Within the specimen assembly, a much higher resistance will exist in the vertical direction than in the horizontal direction; this characteristic enhances the flow in the direction perpendicular to the window. A plane of symmetry in the midplane of the specimen assembly parallel to the reactor window minimizes the effect of contact resistance in that direction.

Assumptions 1 and 2 result in opposite effects on the computation of the maximum temperature in the SSS capsule. Neglecting radiation and convection tends to raise the maximum computed temperature; neglecting contact resistance tends to lower the maximum computed temperature.

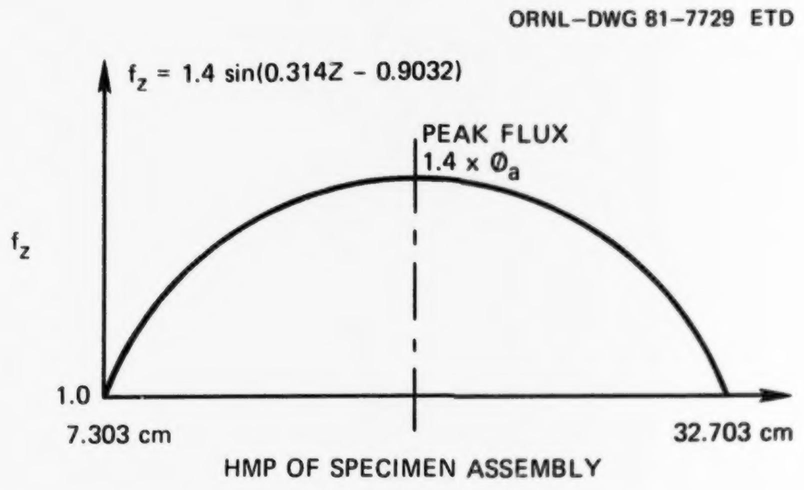

Fig. 10. Z-dependent factor applied to the computed nuclear heating rate.

3. The nuclear heating rate computed for the SSS capsule was five times higher than that computed for the PVWS capsule, and the flexibility of the SSS capsule design was limited in that no internal cooling was possible because of the size restriction. An experiment mocking up the SSS capsule was performed in the ORR PSF to verify that no excessive temperatures would develop with the chosen gas gap and pure helium (Appendix D). The experimental temperature distribution agreed well with the computed temperature distribution that resulted when using the computed nuclear heating rate in a 3-D heat transfer model of the SSS capsule mock-up experiment.

Three sets of computational cases were based on the SSS capsule model:

1. Determination of the front and back gas gaps. The only heat source in this case was the nuclear heating in the steel components. The sweep gas was helium, and the gap was varied by changing the helium conductivity to an equivalent conductivity based on the following relation:

$$k_{eq} = \frac{k_{he} d}{d_o} ,$$

where

d = parametric value of path length,
k_{he} = conductivity of helium,
d_o = grid-fixed path length.

2. Determination of a neon-helium gas mixture. The only heat source in this analysis was the nuclear heating rate in the steel components.

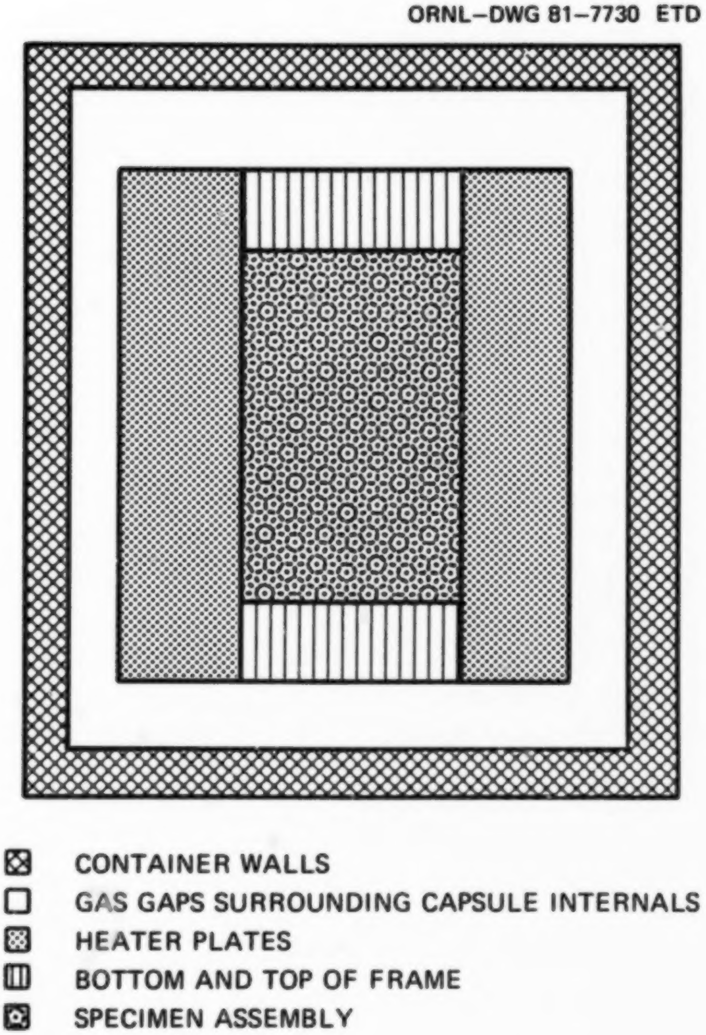
ORNL–DWG 81–7730 ETD
CONTAINER WALLS
GAS GAPS SURROUNDING CAPSULE INTERNALS
HEATER PLATES
BOTTOM AND TOP OF FRAME
SPECIMEN ASSEMBLY

Fig. 11. Two-dimensional XZ geometry heat transfer model of SSS capsule.

The gaps were held at 1.016 mm. A mixture was sought that would bring the temperature near the design temperature in the specimen assembly. Conductivity of the gas mixture is computed in the following way (Appendix C):

$$k_m = f_{he}k_{he} + (1 - f_{he})k_{ne} ,$$

Table 2. Regions' description of the 2-D XZ geometry of the SSS capsule model

Region No.	Material No.[a]	Heat generation No.[b]	Left X [cm (in.)]	Right X [cm (in.)]	Lower Z [cm (in.)]	Upper Z [cm (in.)]
1	1	1	0.0 (0.0)	0.53924 (0.2123)	0.0 (0.0)	39.0525 (15.375)
2	1	1	0.53924 (0.2123)	4.46100 (1.7563)	0.0 (0.0)	0.9525 (0.375)
3	1	1	0.53924 (0.2123)	4.46100 (1.7563)	37.1475 (14.625)	39.0525 (15.375)
4	1	1	4.46100 (1.7563)	5.00 (1.9685)	0.0 (0.0)	39.0525 (15.375)
5	6		0.53924 (0.2123)	0.69164 (0.2723)	0.9525 (0.375)	37.1475 (14.625)
6	2		0.69164 (0.2723)	4.30860 (1.6963)	0.9525 (0.375)	1.5875 (0.625)
7	2		0.69164 (0.2723)	4.30860 (1.6963)	35.8775 (14.125)	37.1475 (14.625)
8	6		4.30860 (1.6963)	4.46100 (1.7563)	0.9525 (0.375)	37.1475 (14.625)
9	3	1	0.69164 (0.2723)	1.23012 (0.4843)	1.5875 (0.625)	35.8775 (14.125)
10	3	1	3.77012 (1.4843)	4.30860 (1.6963)	1.5875 (0.625)	35.8775 (14.125)
11	4	1	1.23012 (0.4843)	3.77012 (1.4843)	1.5875 (0.625)	6.0325 (2.375)
12	4	1	1.23012 (0.4843)	3.77012 (1.4843)	31.4325 (12.375)	35.8775 (14.125)
13	5	1	1.23012 (0.4843)	3.77012 (1.4843)	6.0325 (2.375)	31.4325 (12.375)

[a] 1 = SS304L; 2 = helium, neon, or mixture; 6 = helium, neon, or mixture in front and back gaps; 3 = low-carbon steel in heaters; 4 = low-carbon steel in frame; and 5 = low-carbon steel in specimen assembly.

[b] 1 = Computed nuclear heating rate.

where

f_{he} = fraction of conductivity of helium,
$1 - f_{he}$ = fraction of conductivity of neon in the composite gas,
k_{he} = conductivity of helium,
k_{ne} = conductivity of neon,
k_m = conductivity of mixture.

This simple correlation yields a thermal conductivity value for the mixture that lies between the values for the components of the mixture.

3. Determination of heater power in the heater plates. The total heat generated in the model consists of the computed nuclear heating rate in the steel and a volumetric heat generation simulating the electric heating of the plates. The gap was held at 1.016 mm, and the gas is helium. The volumetric heat generation rate simulating the electric heat in the plates was computed as follows: the heater plate (Fig. 12) was divided into three heater regions (i.e., bottom, top, and middle) so that each would be separately controlled in the computational model (Fig. 13). This division was made to demonstrate that temperatures could be flattened in the specimen assembly. The calculated heat generation rates are 1796 kW/m^3 in the top and bottom heater regions and 1289 kW/m^3 in the middle region, which is approximately a ratio of 1.4 to 1 between the volumetric heat generation rates in the outer and inner heater regions (Appendix C). This distribution was used to compensate for the spatial dependence of the nuclear heating rate. Table 3 summarizes the parameter variations in these sets. Isotherms and temperature profiles for these cases are presented in Figs. A.1 through A.8 of Appendix A.

3.5 Computation Model of the PVWS Capsule

The purpose of the overall PVWS heat transfer model is to determine several design parameters. Parameters other than the water flow in the cooler tubes (which remains constant for all cooler plates — Appendix C) are the front gas gap, the gas annuli surrounding the cooler tubes, the heater power required to heat the specimens and flatten the temperatures, and the possible gas mixtures to be used if enough heat cannot be generated with 100% helium.

A 2-D XZ geometry heat transfer model was developed. The geometric configuration is shown in Fig. 14, and the definition of the regions is given in Table 4. The basic assumptions made for the SSS capsule in Sect. 3.4 are also applicable to this capsule.

The contact resistances in this capsule (which cannot be estimated) were taken into account by reducing the conductivity of the specimen assemblies by 50%. This reduction tends to increase the gradients in the assemblies. Assumptions are that if gradients can be controlled under these conditions, they will also be controlled in the physical conditions present when operating the capsule.

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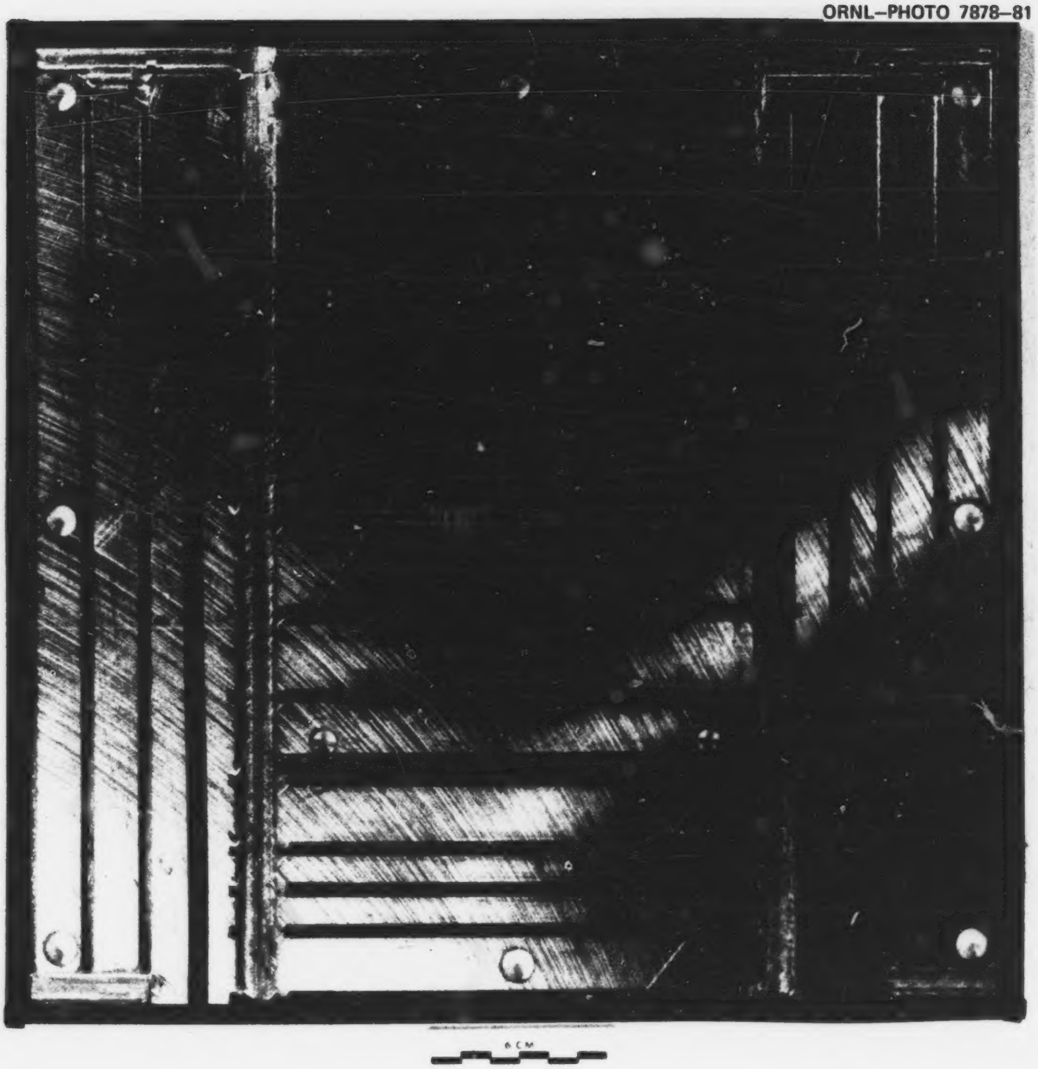

Fig. 12. Photograph of a grooved heater plate with demarcations showing the five repairs.

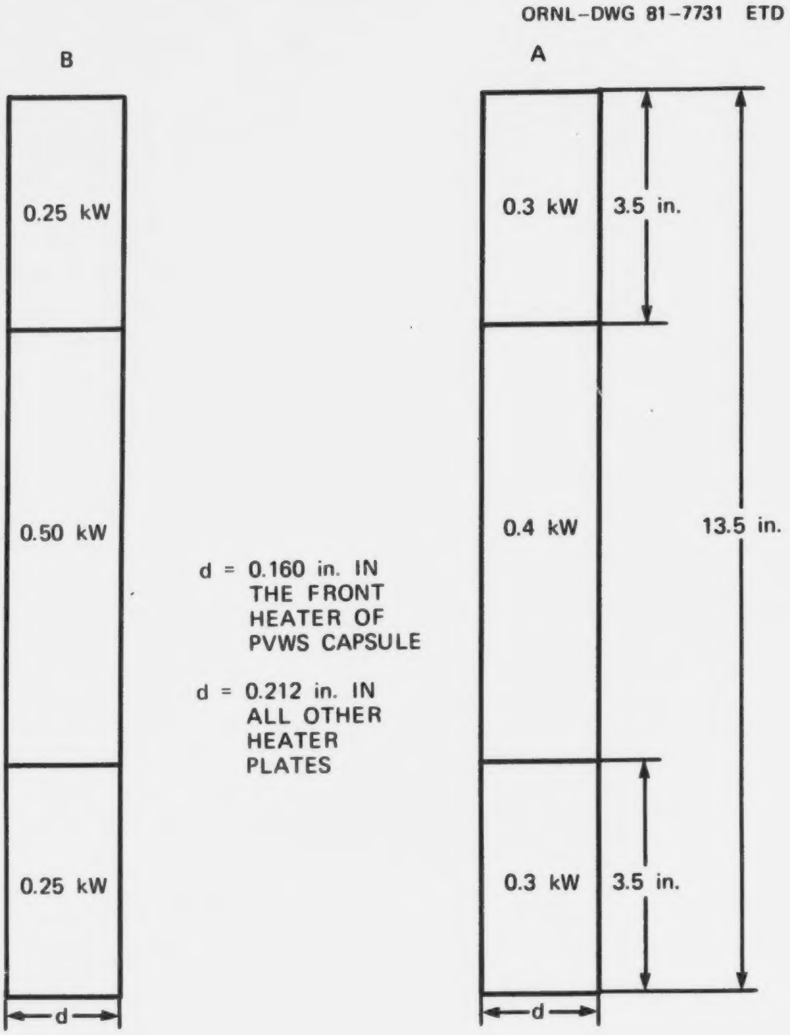
ORNL-DWG 81-7731 ETD
B
A
0.25 kW
0.50 kW
0.25 kW
0.3 kW
0.4 kW
0.3 kW
3.5 in.
3.5 in.
13.5 in.
d = 0.160 in. IN THE FRONT HEATER OF PVWS CAPSULE
d = 0.212 in. IN ALL OTHER HEATER PLATES
d
d

Fig. 13. Z-dependence of electric heat generation rate in heaters.

3.5.1 Effect of nuclear heating rate variation in iron

The most important parameter affecting the thermal behavior of the capsule is the nuclear heating rate in the iron (computation is described in Appendix D). From previous experience, however, this parameter has a high degree of uncertainty in thick slabs of steel so that computed values could be off by as much as 100%. Because a mock-up for an experiment of the PVWS capsule in the ORR PSF was impractical, a parametric study was performed for the PVWS capsule that changed the nuclear heating rates by factors from 1 to 2.25 times the computed values. Table 5 summarizes the cases studied with nuclear heating rate variation. Isotherms and profiles for this study are presented in Figs. A.9 through A.15 of Appendix A.

Table 3. Summary of cases for the SSS capsule

Case No.	Parameter value	Figures		Case description
		Isotherms	Profiles	
1	0.0889 cm (0.035 in.)	A.1	A.3	Front and back gap-thickness variation; helium sweep gas; nuclear heating only
2	0.1016 cm (0.040 in.)			
3	0.1143 cm (0.045 in.)			
4	0.127 cm (0.050 in.)	A.2	A.5	
5	0.1524 cm (0.060 in.)			
	(He/Ne)			
6	0.90/0.10	A.4	A.6	Gas conductivity variation; gap thickness = 0.035 in.
7	0.80/0.20			
8	0.75/0.25			
9	0.70/0.30	A.5	A.6	
10	1.0 kW/plate	A.7	A.8	Electric power variation with nuclear heating; helium sweep gas; gap thickness = 0.035 in.
11	0.75 kW/plate			
12	0.50 kW/plate			
13	0.25 kW/plate			

3.5.2 Determination of the front gas gap

The front surface together with the cooler tubes provide the main heat sinks for the heat generated in the capsule. To maintain the design temperature, a gas gap must be designed to prevent sharp gradients from occurring in the specimen assemblies. Because the gap is modeled in the correct geometry, changes to the basic model gap size were made by modifying the gas conductivity to simulate the change in path length by

$$\frac{k_1 \cdot A_1 \cdot \Delta T}{d_1} = \frac{k_2 \cdot A_1 \cdot \Delta T}{d_2} ,$$

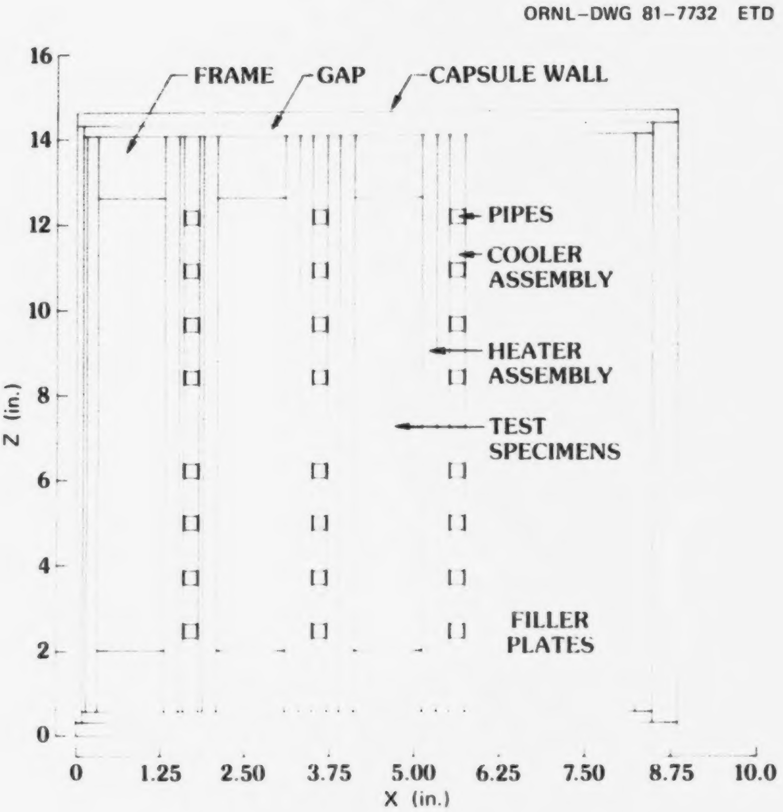
ORNL-DWG 81-7732 ETD
FRAME
GAP
CAPSULE WALL
PIPES
COOLER ASSEMBLY
HEATER ASSEMBLY
TEST SPECIMENS
FILLER PLATES
Z (in.)
16
14
12
10
8
6
4
2
0
0
1.25
2.50
3.75
5.00
6.25
7.50
8.75
10.0
X (in.)

Fig. 14. Two-dimensional XZ geometry heat transfer model of the PVWS capsule.

where

k_1 = conductivity of gas used,
k_2 = effective conductivity to be computed,
A_1 = cross-sectional heat transfer area,
ΔT = temperature difference across path length,
d_1 = heat transfer path length in basic model, and
d_2 = heat transfer path length for particular case.

Because the cross-sectional areas and the temperature differences should be the same, we obtain the following relation for the effective conductivity:

$$k_2 = \frac{k_1 d_2}{d_1} \cdot$$

Table 4. Regions' description of the 2-D XZ geometry of the PVWS capsule

Region No.	Material No.[a]	Heat generation No.[b]	Left X [cm (in.)]	Right X [cm (in.)]	Lower Z [cm (in.)]	Upper Z [cm (in.)]
			Stainless steel container			
1	1	1	0.0 (0.0)	22.4790 (8.85)	0.0 (0.0)	0.9525 (0.375)
2	1	1	0.0 (0.0)	0.2286 (0.090)	0.9525 (0.375)	38.9255 (15.325)
3	1	1	0.0 (0.0)	22.4790 (8.85)	38.9255 (15.325)	40.6400 (16.0)
4	1	1	21.5265 (8.475)	22.4790 (8.85)	0.9525 (0.375)	38.9255 (15.325)
			Gaps surrounding PVWS capsule internals			
5	2	1	0.2286 (0.090)	21.5265 (8.475)	0.9525 (0.375)	2.8575 (1.125)
6	3	1	0.2286 (0.090)	0.3810 (0.15)	2.8575 (1.125)	37.1475 (14.625)
7	2	1	0.2286 (0.090)	21.5265 (8.475)	37.1475 (14.625)	38.9255 (15.325)
8	2	1	19.6215 (7.725)	21.5265 (8.475)	2.8575 (1.125)	37.1475 (14.625)
			Heater plate assemblies			
9	4	1	0.3810 (0.15)	0.7874 (0.31)	2.8575 (1.125)	37.1475 (14.625)
10	4	1	3.3274 (1.31)	3.8659 (1.522)	2.8575 (1.125)	37.1475 (14.625)
11	4	1	4.7549 (1.872)	5.2934 (2.084)	2.8575 (1.125)	37.1475 (14.625)
12	4	1	7.8334 (3.084)	8.3718 (3.296)	2.8575 (1.125)	37.1475 (14.625)
13	4	1	9.8958 (3.896)	10.4343 (4.108)	2.8575 (1.125)	37.1475 (14.625)
14	4	1	12.9743 (5.108)	13.5128 (5.32)	2.8575 (1.125)	37.1475 (14.625)
			Specimen assemblies			
15	5	1	0.7874 (0.31)	3.3274 (1.31)	2.8575 (1.125)	37.1475 (14.625)
16	5	1	5.2934 (2.084)	7.8334 (3.084)	2.8575 (1.125)	37.1475 (14.625)
17	5	1	10.4343 (4.108)	12.9743 (5.108)	2.8575 (1.125)	37.1475 (14.625)
			Steel in cooler plates			
18	4	1	3.8659 (1.522)	4.0836 (1.6077)	2.8575 (1.125)	37.1475 (14.625)
19	4	1	4.5375 (1.7864)	4.7549 (1.872)	2.8575 (1.125)	37.1475 (14.625)
20	4	1	8.3718 (3.296)	8.9070 (3.5067)	2.8575 (1.125)	37.1475 (14.625)
21	4	1	9.3609 (3.6854)	9.8958 (3.896)	2.8575 (1.125)	37.1475 (14.625)
22	4	1	13.5128 (5.32)	14.0480 (5.5307)	2.8575 (1.125)	37.1475 (14.625)
23	4	1	14.5026 (5.7094)	15.0368 (5.92)	2.8575 (1.125)	37.1475 (14.625)
24	4	1	4.0836 (1.6077)	4.5375 (1.7864)	2.8575 (1.125)	6.2536 (2.462)
25	4	1	4.0836 (1.6077)	4.5375 (1.7864)	7.0819 (2.78815)	10.0636 (3.96205)
26	4	1	4.0836 (1.6077)	4.5375 (1.7864)	10.8919 (4.28815)	13.8336 (5.46205)
27	4	1	4.0836 (1.6077)	4.5375 (1.7864)	14.7019 (5.78815)	17.6836 (6.96205)
28	4	1	4.0836 (1.6077)	4.5375 (1.7864)	18.5119 (7.28815)	21.4936 (8.46205)

Table 4 (continued)

Region No.	Material No.[a]	Heat generation No.[b]	Left X [cm (in.)]	Right X [cm (in.)]	Lower Z [cm (in.)]	Upper Z [cm (in.)]
			Steel in cooler plates (continued)			
29	4	1	4.0836 (1.6077)	4.5375 (1.7864)	22.3219 (8.78815)	25.3036 (9.96205)
30	4	1	4.0836 (1.6077)	4.5375 (1.7864)	26.1319 (10.28815)	29.1136 (11.46205)
31	4	1	4.0836 (1.6077)	4.5375 (1.7864)	29.9419 (11.78815)	32.9236 (12.96205)
32	4	1	4.0836 (1.6077)	4.5375 (1.7864)	33.7519 (13.28815)	37.1475 (14.625)
33	4	1	8.9070 (3.5067)	9.3609 (3.6854)	2.8575 (1.125)	6.2536 (2.46025)
34	4	1	8.9070 (3.5067)	9.3609 (3.6854)	7.0819 (2.78815)	10.0636 (3.96205)
35	4	1	8.9070 (3.5067)	9.3609 (3.6854)	10.8919 (4.28815)	13.8336 (5.46205)
36	4	1	8.9070 (3.5067)	9.3609 (3.6854)	14.7019 (5.78815)	17.6836 (6.96205)
37	4	1	8.9070 (3.5067)	9.3609 (3.6854)	18.5119 (7.28815)	21.4936 (8.46205)
38	4	1	8.9070 (3.5067)	9.3609 (3.6854)	22.3219 (8.78815)	25.3036 (9.96205)
39	4	1	8.9070 (3.5067)	9.3609 (3.6854)	26.1319 (10.78815)	29.1136 (11.46205)
40	4	1	8.9070 (3.5067)	9.3609 (3.6854)	29.9419 (11.78815)	32.9236 (12.96205)
41	4	1	8.9070 (3.5067)	9.3609 (3.6854)	33.7519 (13.28815)	37.1475 (14.625)
42	4	1	14.0480 (5.5307)	14.5019 (5.7094)	2.8575 (1.125)	6.2536 (2.46205)
43	4	1	14.0480 (5.5307)	14.5019 (5.7094)	7.0819 (2.78815)	10.0636 (3.96205)
44	4	1	14.0480 (5.5307)	14.5019 (5.7094)	10.8919 (4.28815)	13.8336 (5.46205)
45	4	1	14.0480 (5.5307)	14.5019 (5.7094)	14.7019 (5.78815)	17.6836 (6.96205)
46	4	1	14.0480 (5.5307)	14.5019 (5.7094)	18.5119 (7.28815)	21.4936 (8.46205)
47	4	1	14.0480 (5.5307)	14.5019 (5.7094)	22.3219 (8.78815)	25.3036 (9.96205)
48	4	1	14.0480 (5.5307)	14.5019 (5.7094)	26.1319 (10.28815)	29.1136 (11.46205)
49	4	1	14.0480 (5.5307)	14.5019 (5.7094)	29.9419 (11.78815)	32.9236 (12.96205)
50	4	1	14.0480 (5.5307)	14.5019 (5.7094)	33.7519 (13.28815)	37.1475 (14.625)
			Annuli in first cooler plate			
51	6		4.0836 (1.6077)	4.1344 (1.6277)	6.2537 (2.4621)	7.0818 (2.7881)
52	6		4.0836 (1.6077)	4.1344 (1.6277)	10.0637 (3.9621)	10.8918 (4.2881)
53	6		4.0836 (1.6077)	4.1344 (1.6277)	13.8737 (5.4621)	14.7018 (5.7881)
54	6		4.0836 (1.6077)	4.1344 (1.6277)	17.6837 (6.9621)	18.5118 (7.2881)
55	6		4.0836 (1.6077)	4.1344 (1.6277)	21.4937 (8.4621)	22.3218 (8.7881)
56	6		4.0836 (1.6077)	4.1344 (1.6277)	25.3037 (9.9621)	26.1318 (10.2881)
57	6		4.0836 (1.6077)	4.1344 (1.6277)	29.1137 (11.4621)	29.9418 (11.7881)
58	6		4.0836 (1.6077)	4.1344 (1.6277)	32.9237 (12.9621)	33.7518 (13.2881)
59	6		4.4867 (1.7664)	4.5375 (1.7864)	6.2537 (2.4621)	7.0818 (2.7881)
60	6		4.4867 (1.7664)	4.5375 (1.7864)	10.0637 (3.9621)	10.8918 (4.2881)
61	6		4.4867 (1.7664)	4.5375 (1.7864)	13.8737 (5.4621)	14.7018 (5.7881)
62	6		4.4867 (1.7664)	4.5375 (1.7864)	17.6837 (6.9621)	18.5118 (7.2881)
63	6		4.4867 (1.7664)	4.5375 (1.7864)	21.4937 (8.4621)	22.3218 (8.7881)
64	6		4.4867 (1.7664)	4.5375 (1.7864)	25.3037 (9.9621)	26.1318 (10.2881)
65	6		4.4867 (1.7664)	4.5375 (1.7864)	29.1137 (11.4621)	29.9418 (11.7881)
66	6		4.4867 (1.7664)	4.5375 (1.7864)	32.9237 (12.9621)	33.7518 (13.2881)

Table 4 (continued)

Region No.	Material No.[a]	Heat generation No.[b]	Left X [cm (in.)]	Right X [cm (in.)]	Lower Z [cm (in.)]	Upper Z [cm (in.)]
			Annuli in second cooler plate			
67	7		8.9070 (3.5067)	8.9578 (3.5267)	6.2537 (2.4621)	7.0818 (2.7881)
68	7		8.9070 (3.5067)	8.9578 (3.5267)	10.0637 (3.9621)	10.8918 (4.2881)
69	7		8.9070 (3.5067)	8.9578 (3.5267)	13.8737 (5.4621)	14.7018 (5.7881)
70	7		8.9070 (3.5067)	8.9578 (3.5267)	17.6837 (6.9621)	18.5118 (7.2881)
71	7		8.9070 (3.5067)	8.9578 (3.5267)	21.4937 (8.4621)	22.3218 (8.7881)
72	7		8.9070 (3.5067)	8.9578 (3.5267)	25.3037 (9.9621)	26.1318 (10.2881)
73	7		8.9070 (3.5067)	8.9578 (3.5267)	29.1137 (11.4621)	29.9418 (11.7881)
74	7		8.9070 (3.5067)	8.9578 (3.5267)	32.9237 (12.9621)	33.7518 (13.2881)
75	7		9.3101 (3.6654)	9.3609 (3.6854)	6.2537 (2.4621)	7.0818 (2.7881)
76	7		9.3101 (3.6654)	9.3609 (3.6854)	10.0637 (3.9621)	10.8918 (4.2881)
77	7		9.3101 (3.6654)	9.3609 (3.6854)	13.8737 (5.4621)	14.7018 (5.7881)
78	7		9.3101 (3.6654)	9.3609 (3.6854)	17.6837 (6.9621)	18.5118 (7.2881)
79	7		9.3101 (3.6654)	9.3609 (3.6854)	21.4937 (8.4621)	22.3218 (8.7881)
80	7		9.3101 (3.6654)	9.3609 (3.6854)	25.3037 (9.9621)	26.1318 (10.2881)
81	7		9.3101 (3.6654)	9.3609 (3.6854)	29.1137 (11.4621)	29.9418 (11.7881)
82	7		9.3101 (3.6654)	9.3609 (3.6854)	32.9237 (12.9621)	33.7518 (13.2881)
			Annuli in third cooler plate			
83	8		14.0480 (5.5307)	14.0988 (5.5507)	6.2537 (2.4621)	7.0818 (2.7881)
84	8		14.0480 (5.5307)	14.0988 (5.5507)	10.0637 (3.9621)	10.8918 (4.2881)
85	8		14.0480 (5.5307)	14.0988 (5.5507)	13.8737 (5.4621)	14.7018 (5.7881)
86	8		14.0480 (5.5307)	14.0988 (5.5507)	17.6837 (6.9621)	18.5118 (7.2881)
87	8		14.0480 (5.5307)	14.0988 (5.5507)	21.4937 (8.4621)	22.3218 (8.7881)
88	8		14.0480 (5.5307)	14.0988 (5.5507)	25.3037 (9.9621)	26.1318 (10.2881)
89	8		14.0480 (5.5307)	14.0988 (5.5507)	29.1137 (11.4621)	29.9418 (11.7881)
90	8		14.0480 (5.5307)	14.0988 (5.5507)	32.9237 (12.9621)	33.7518 (13.2881)
91	8		14.4511 (5.6894)	14.5019 (5.7094)	6.2537 (2.4621)	7.0818 (2.7881)
92	8		14.4511 (5.6894)	14.5019 (5.7094)	10.0637 (3.9621)	10.8918 (4.2881)
93	8		14.4511 (5.6894)	14.5019 (5.7094)	13.8737 (5.4621)	14.7018 (5.7881)
94	8		14.4511 (5.6894)	14.5019 (5.7094)	17.6837 (6.9621)	18.5118 (7.2881)
95	8		14.4511 (5.6894)	14.5019 (5.7094)	21.4937 (8.4621)	22.3218 (8.7881)
96	8		14.4511 (5.6894)	14.5019 (5.7094)	25.3037 (9.9621)	26.1318 (10.2881)
97	8		14.4511 (5.6894)	14.5019 (5.7094)	29.1137 (11.4621)	29.9418 (11.7881)
98	8		14.4511 (5.6894)	14.5019 (5.7094)	32.9237 (12.9621)	33.7518 (13.2881)

[a] 1 = SS304L, 2 = gas, 3 = gas in front gap, 4 = low-carbon steel, 5 = low-carbon steel (specimen assemblies), 6 = gas in annuli of first cooler plate, 7 = gas in annuli of second cooler plate, and 8 = gas in annuli of third cooler plate.

[b] 1 = nuclear heating rate only.

Table 5. Summary of cases for the PVWS capsule nuclear heating rate variation

Case No.	Parameter value C[a]	Figures		Case description
		Isotherms	Profiles	
1	1.0	A.9	A.11	Helium sweep gas
2	1.25			
3	1.5			
4	1.75			
5	2.0			
6	2.25			
7	2.25	A.40	A.11	
8	1.0	A.12	A.14	Neon sweep gas
9	1.25			
10	1.5			
11	1.75	A.13	A.14	

[a] Nuclear heating rate value = C × computed value.

Table 6 summarizes the case studies for the front gas gap variation. No substantial temperature variations were observed; therefore, the isotherms of Fig. A.9 (Appendix A) are representative of the typical temperature distribution.

3.5.3 Determination of the annular gas gap thickness surrounding the cooler tubes

A special model to describe the cylindrical annulus and tube of a cooler plate in an XZ geometry had to be developed. Because the problem is a steady-state problem, the main concern is to maintain heat transfer areas and path lengths equivalent in both geometries. The difference in volumes affecting the nuclear heat generated in the model due to this simulation is negligible.

Figure 15 represents the actual Rθ cross section through a tube annulus in a plate configuration and the XZ model representation of that cross section.

To account for the reduction in cross-sectional area from the outer radius to the inner radius of the annulus, an average cross-sectional area was computed as

$$A_a = \frac{\pi(D_1 + D_2)}{2} L ,$$

Table 6. Summary of cases for the PVWS capsule front gas gap-thickness variation

Case No.	Parameter value [cm (in.)]	Figures		Case description
		Isotherms	Profiles	
12	0.0889 (0.035)			Computed nuclear heating rate; helium sweep gas; 0.020 annular gap thickness; no electric heat
13	0.1016 (0.040)			
14	0.1143 (0.045)			
15	0.127 (0.050)			
16	0.1524 (0.060)	A.9	A.11	
17	0.1778 (0.070)			
18	0.2032 (0.080)			
19	0.2286 (0.090)			

where

A_a = average cross-sectional area of the annulus,
D_1 = ID of the annulus,
D_2 = OD of the annulus, and
L = length of tube to be considered = 1 unit in the Y direction.

The total circumference of the equivalent area was equally divided between both sides (Fig. 15). To avoid additional contact area between the steel and the gas, a 0.000254-mm-void gap was established between the top and bottom of the annulus and the adjacent steel. Also the area between the two sides of the annulus simulation was left void, and a forced-convection boundary condition was applied at the inner boundary of the annulus as indicated on Fig. 15. However, because the inner cross-sectional area of the tube is smaller than the area in the model, an adjustment has been made to the forced convection heat transfer coefficient:

$$h_t \cdot A_t \cdot \Delta T = h_m \cdot A_m \cdot \Delta T \ ,$$

and

$$h_m = \frac{h_t \cdot A_t}{A_m} \ ,$$

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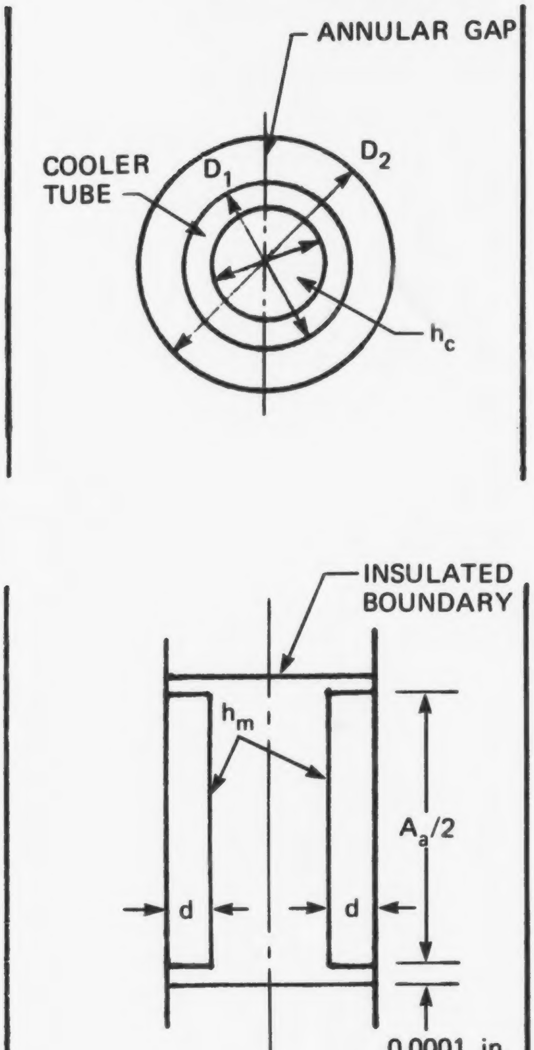
ANNULAR GAP
COOLER TUBE
D1
D2
hc
INSULATED BOUNDARY
hm
Aa/2
d
d
0.0001 in. VOID GAP

Fig. 15. Rectangular representation of Rθ cross section of annular gap surrounding a cooler tube in an XZ geometry.

where

h_t = computed forced-convection heat transfer coefficient in the tube,
h_m = effective forced-convection heat transfer coefficient for computer model,
A_t = cross-sectional heat transfer area inside tube,

A_m = cross-sectional heat transfer area for forced convection in model, and

ΔT = temperature difference from inner tube surface to bulk water temperature (should remain the same for the model).

Further analysis (Appendix C) comparing the effective conductance of the tube and convection boundary condition in series showed a 1.5% reduction in the total conductance and was assumed negligible.

This model conveniently handles the parametric study of the annulus thickness variation, because the only change that needs to be made in the model is in changing the six grid lines determining the annulus thickness. By incorporating all these simulations, both the cross-sectional areas and the path lengths through the annuli are preserved. By insulating the proper parts from the steel, all heat is forced through the annuli or the outer surfaces of the capsules into the proper heat sinks in the correct proportions.

Table 7 summarizes the cases studied with annular gas gap thickness variation. Isotherms and temperature profiles are presented in Figs. A.15 and A.16 of Appendix A.

Table 7. Summary of cases for the PVWS capsule annular gas gap-thickness variation

Case No.	Parameter value [cm (in.)]	Figures		Case description
		Isotherms	Profiles	
20	0.0381 (0.015)	A.15		Computed nuclear heating rate; helium sweep gas; 0.1524 (0.060) front gas gap; no electric heating
21	0.0508 (0.020)			
22	0.0635 (0.025)	A.16		
23	0.0762 (0.030)			

3.5.4 Effects of gas mixture conductivity variation

The effect of using helium and neon gas mixtures in the gaps was also studied. A subroutine (Appendix B) calculates a conductivity for the gas in the following manner:

$$k_m = f_{he}k_{he} + (1 - f_{he})k_{ne} ,$$

where

k_m = conductivity of the helium-neon mixture,
f_{he} = conductivity fraction of helium,
k_{he} = conductivity of the helium, and
k_{ne} = conductivity of the neon.

This correlation was based on the assumption that some mixture of helium and neon will produce such a conductivity (since it lies between the two pure gas conductivities), and the mixture itself is not considered as a parameter in the design.

The summary of this analysis is presented in Table 8. Isotherms and profiles are presented in Fig. A.17 through A.20.

3.5.5 Determination of maximum required heater power

The configuration of the heater plate (Fig. 12) shows five independently controlled heater regions in each plate arranged as indicated. Because the model is an XZ model, the heaters were modeled by three regions: top, middle, and bottom (Fig. 13). The bottom and top regions have the same volume. Because the nuclear heating rates are 1.4 times higher in the middle of the specimen assembly than at the edges, a ratio of ~1.4:1 was chosen between the volumetric heat generation in the top

Table 8. Summary of cases for the PVWS capsule gas-mixture conductivity variation

Case No.	Parameter value	Figures		Case description
		Isotherms	Profiles	
	He/Ne			
24	0.05/0.95	A.17	A.20	The mixture conductivity is given in Section 3.5.4; computed nuclear heating rate; 0.1524-cm front gap thickness; 0.0508-cm annular gap thickness
25	0.1/0.9			
26	0.15/0.85			
27	0.2/0.8			
28	0.25/0.75	A.18	A.20	
29	0.30/0.70			
30	0.35/0.65			
31	0.4/0.6			
32	0.45/0.55			
33	0.5/0.5	A.19	A.20	

and bottom region to that in the middle region. To facilitate the parametric study, a basic heat generation rate was chosen to produce 1 kW of power in the whole plate. The top and bottom parts produce 0.3 kW each, and the middle part produces 0.4 kW. The front heater plate differs in thickness from the other five plates so that a different volumetric heat generation rate has to be computed for it. The front heater plate is 4.064 mm thick, and the rest of the heater plates are 5.385 mm thick.

The volumetric heat generation rates in the front heater are 2379 kW/m^3 in the top and bottom regions and 1707 kW/m^3 in the middle region. The volumetric heat generation rates in the other heater plates are 1796 kW/m^3 in the top and bottom heater regions and 1289 kW/m^3 in the middle region.

A user-supplied subroutine (Appendix B) was written to apply a Z-dependent heat generation function in the heater plates, in addition to the internal nuclear heat generation rate. The option of increasing or decreasing the total electric heat generated in a plate, while maintaining the same proportion between the regions, is accomplished by using the constant factor in the appropriate heat generation function definition. The heat generated in a node is then computed by

$$\dot{Q}_0 = (f_c \, \dot{q}0'''_e + \dot{q}0'''_n) \, V_0 \, ,$$

where

$\dot{Q}_0$ = heat generated at node 0 of region m,
f_c = constant input value for the heat generation function associated with region m,
$\dot{q}0'''_e$ = volumetric electric heat generation rate Z-dependent component associated with region m,
$\dot{q}0'''_n$ = volumetric nuclear heat generation rate (X and Z dependent)
V_0 = volume associated with node 0.

Note that $\dot{Q}_0$ may be a sum of up to four terms because the node definitions in HEATING5 are at grid-line intersections; therefore, a volume of a node (in two dimensions) may be composed of four different bordering regions. The summary of cases with variable electric power is given in Table 9. Isotherms and temperature profiles are presented in Figs. A.21 through A.31.

4. DETERMINATION OF THE FINAL DESIGN

The final design of the two capsules was determined so that the fixed parameters (gap sizes, total heating and cooling capacity) in combination with the variable parameters (gas-mixture conductivities and variable heater control) would have a considerable margin in providing the required thermal control under the circumstances encountered in the experiment.

The sensitivity study summary (Figs. 16 and 17) is obtained by using the smallest value of the particular parameter under consideration, P_0,

Table 9. Summary of cases for the PVWS capsule volumetric electric heating rate variation

0.1524-cm front gap thickness
0.0508-cm annular gap thickness

Case No.[a]	Parameter value[b] L,M,N	Figures		Case description
		Isotherms	Profiles	
34	1,1,1			Helium sweep gas
35				
36	2,2,2	A.21	A.22	
37	3,3,3			
38	1,1,1			Neon sweep gas
39	2,2,2	A.22	A.23	
40	1,1,1			Helium sweep gas
41	2,2,2			
42	3,3,3	A.20		
	4,4,4			
43	5,5,5			
44	1,1,1			Average helium — neon conductivity
45	2,2,2			
46	3,3,3	A.19	A.21	
47	4,4,4			
48	5,5,5			
49	1,2,3	A.27	A.31	Helium sweep gas
50	0.5,1.5,2.5	A.28		
51	0.5,1.5,3.5	A.29	A.31	
52	0.5,1.5,3.5	A.30	A.31	The spatial distribution of heat in all the plates was changed to that of Fig. 13(b)

[a] Cases 34 through 48 represent cases with (1) no nuclear heating and (2) spacial distribution of electric power as described in Fig. 13(a). Cases 49 through 52 represent cases that include the computed nuclear heating rate.

[b] Parameter variation L, M, N: L = total heater power in the 0-T position, M = total heater power in the 1/4-T position, and N = total heater power in the 1/2-T position. Power units in kW.

and relating the other values to it (i.e., P/P_0). The vertical axis presents the maximum temperature in the specimen assemblies obtained for that particular case.

The sensitivity study for the SSS capsule (Fig. 16) indicates that, because of the high predicted nuclear heating rate and physical limitations on the dimensions of the system, the smallest possible front and back gap thicknesses (from a fabrication point of view) should be chosen. Because of the uncertainty in the computed nuclear heating rate and the computed temperature distribution, a mock-up experiment of the SSS capsule

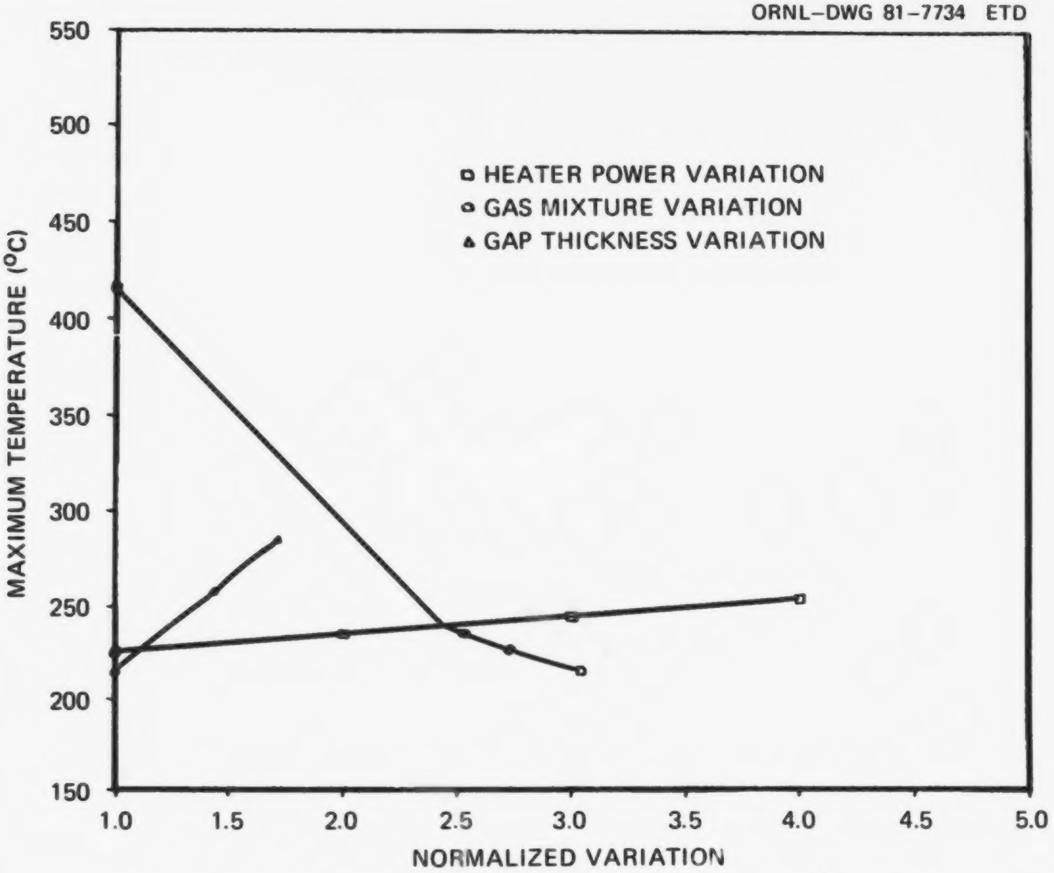

Fig. 16. Sensitivity study with all parameter variations in the SSS capsule.

was performed in the ORR PSF (Appendix D). The computational model in conjunction with that experiment confirmed that a gap size of 0.889 mm would allow enough electric heat to be used to control the temperature at 288°C ± 10°C.

The sensitivity study for the PVWS capsule (Fig. 17) indicates that the gap sizes of the given order of magnitude are not of critical importance except in acting as a buffer between the desired temperature of 288°C and the water temperature of about 40°C. Because these parameters are fixed once the capsule is built, the consideration of minimizing material other than steel in the capsule dictated a front gap thickness of 1.524 mm and an annular gap thickness of 0.508 mm. An annular gap size of 0.635 mm in the back cooler plate was chosen because most of the nuclear interactions are attenuated in the front part of the capsule (Fig. 9).

With fixed gap sizes and a heat transfer coefficient of 5680 $W/m^2 \cdot °C$, the basic model also indicates that the PVWS capsule can operate with helium at >2.5 times the computed nuclear heating rate. With (1) the ORR

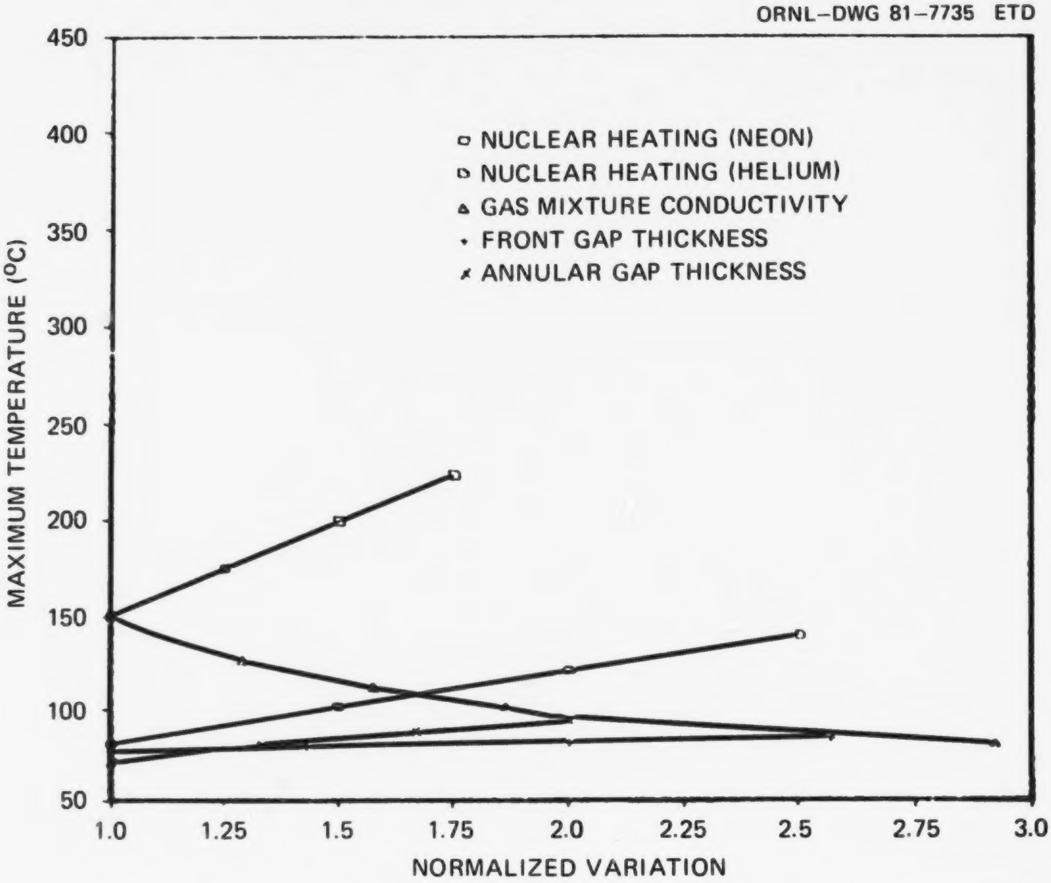

Fig. 17. Sensitivity study with all parameter variations (except electric power) in a PVWS specimen assembly.

operating at full power (30 MW), (2) helium used as sweep gas, and (3) no electric heating, temperatures obtained at the first start-up of the experiment indicate that the computed nuclear heating rate is not a reliable input parameter in the thermal analysis (see comparison of experimental and computed temperatures for the same conditions in Table 10). These data support the range selection in the parametric study of the nuclear heating rate variation in the PVWS capsule. This choice assured that the desired control would be achieved.

However, by anticipating a possible experimental condition wherein nuclear heating in the PVWS is negligible (while the cooling rate is fixed at 5680 W/m^2·°C), we needed to determine an electric heating capacity that would heat all the specimen assemblies to 288°C. Figure 18 indicates that the required temperature of 288°C can be achieved with a total heater power of between 12 and 18 kW with helium as sweep gas. The total heating rate required is about 15 kW. The heater plates were designed to control edge effects and other effects due to the nonuniform

Table 10. SSS and PVWS capsules' recorded vs computed temperatures with nuclear heating, helium sweep gas, and no electric heating

Recorded temperatures							Computed temperatures correspond to center columns
Front thermocouples			Back thermocouples				
257	270	244		260		← SSS →	204
145	146	141		144		← PVWS 0T →	84
122	126	121		122		← PVWS 1/4T →	81
101	101	100		98		← PVWS 1/2T →	75
			270		257		
			147		[a]		
268		240	123		120		
145		141	99		97		
120		118					
97		95					
	266		280	259	254		216
	139		147	145	143		87
	121		119	116	118		81
	93		96	95	95		75
270		241					
143		137					
117		116	274		250		
95		96	143		137		
			116		115		
			94		92		
250	265	234		258			202
138	139	132		[a]			85
116	119	113		115			81
[a]	97	92		94			75

[a]Failed thermocouples.

nuclear heating and unaccounted for structural details. Therefore, the heater plates (Fig. 12) consist of five individually controlled regions, one on each of the four sides and one in the central region of the plate. Figures 19 and 20 demonstrate the effect on the temperature gradients in the specimen assemblies caused by a varying distribution of heat loads in the plates.

With the above combination of parameters assuring control of the specimen assemblies at 288°C ± 10°C, the gas mixture conductivity becomes a parameter that expands the range of conditions for which the temperature control is possible. The primary effect of applying gas mixtures is in reducing the heater loads necessary to maintain a flat temperature distribution in the specimen assemblies. This results in a reduction in possible heater failures during the experiment operation period. If a heater should fail in a circuit, the load on the parallel heater in that circuit would have to be increased. Then, if necessary, the gas mixture could be changed to compensate for heater loss.

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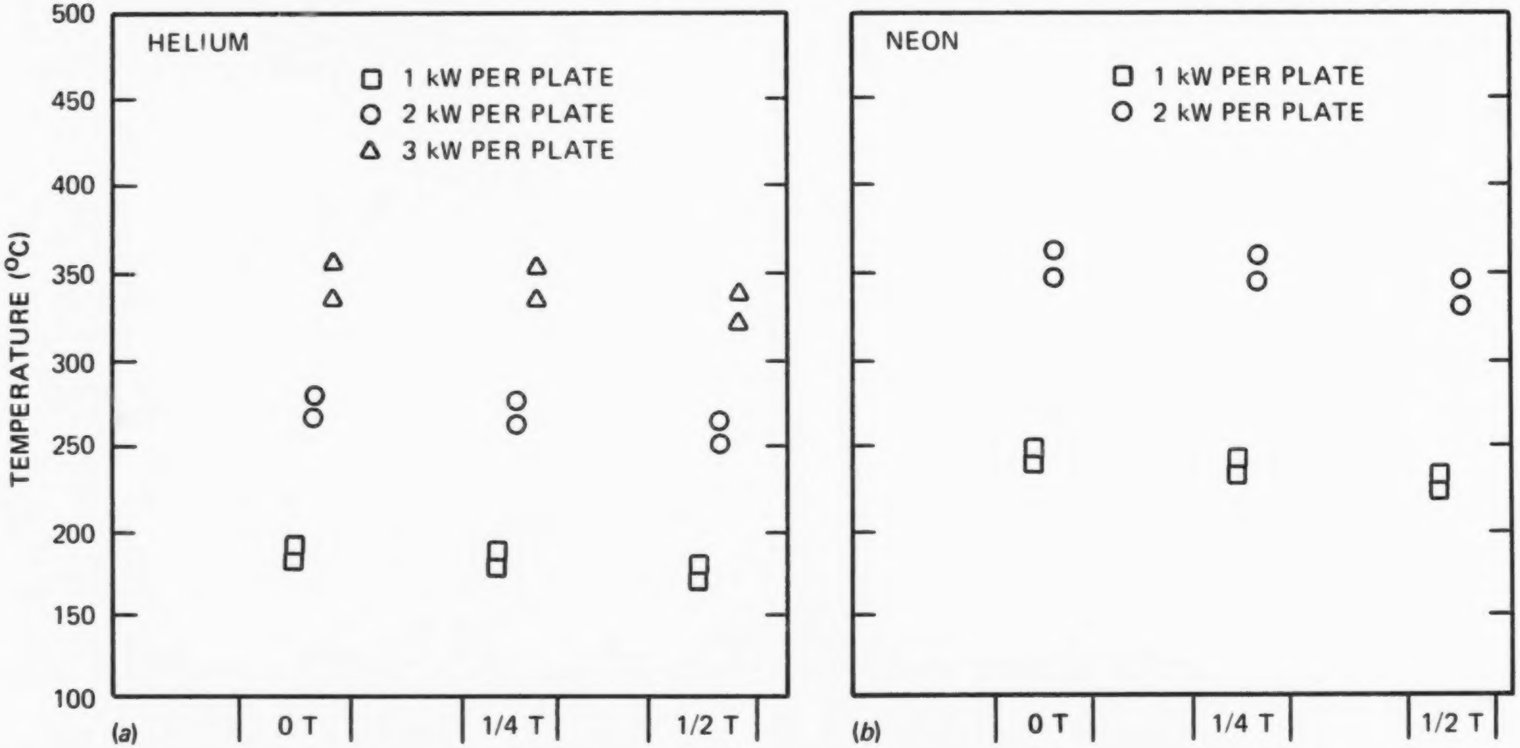

Fig. 18. Sensitivity of temperatures in specimen assemblies of PVWS capsule to electric power variations without nuclear heating. The pairs of points present the minimum and maximum temperatures computed at that location under the same conditions.

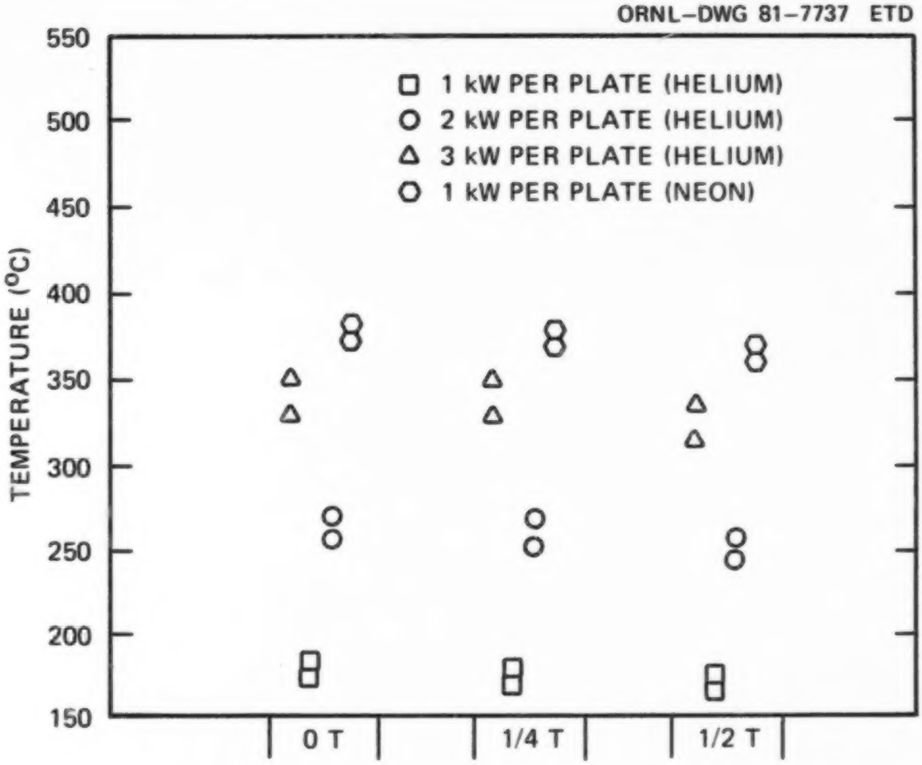

Fig. 19. Sensitivity of temperatures in specimen assemblies of PVWS capsule to electric power variations with nuclear heating.

5. CONCLUSIONS

As a result of the extensive sensitivity study of both the SSS and the PVWS capsules, a high flexibility design was obtained. The two basic mathematical models provided an efficient tool in determining the final design parameters.

The primary reason for the extensive study was the high degree of uncertainty associated with the calculated nuclear heating rates in the steel components. This heating rate, which is space and also slightly time dependent, has a major effect on the thermal behavior of the capsules.

Considering the results of the sensitivity study for the SSS capsule, these conclusions were reached.

1. A gap thickness of 0.889 mm is sufficient (supported by the SSS capsule mock-up experiment) to remove the nuclear heat without exceeding the design temperature of 288°C.
2. A heater capacity of 5 kW per heater plate with five independently controlled heater regions is sufficient to maintain the specimens at the desired temperature in the absence of nuclear heating.

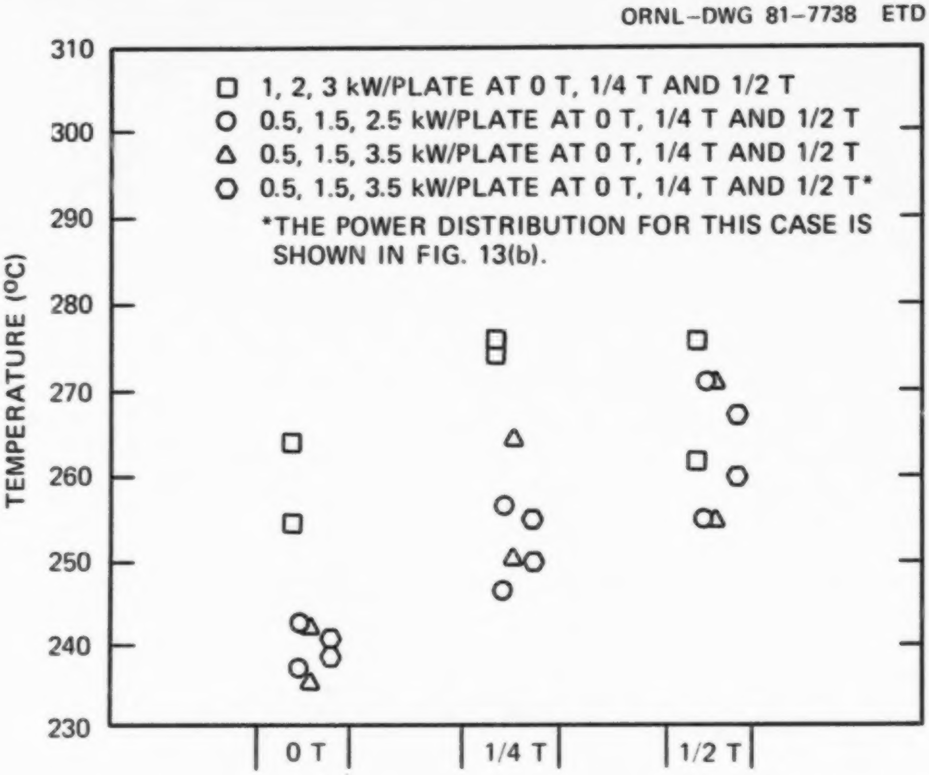

Fig. 20. Sensitivity of temperatures in specimen assemblies of PVWS capsule to power variations in the different positions as well as changes in power distribution within the plates.

3. According to the computational model and the mock-up experiment, this capsule will run with pure helium to allow for use of electric heating to maintain a flat temperature distribution in the specimen assembly.

The SSS capsules are designed to correlate with each of the three specimen assemblies in the PVWS capsule. Therefore, at least three SSS capsules will be used during the 20 months of the experiment. The first capsule has already been removed and disassembled. The SSS capsule was operating on pure helium, and temperatures were being controlled with electric heat to maintain the design temperature distribution of 288°C ± 10°C.

Considering the results of the sensitivity study for the PVWS capsule, the following conclusions were reached:

1. In combination with (1) a 0.508-mm annular gap thickness in the front and middle cooler plates, (2) a 0.635-mm annular gap thickness in the back cooler plate, and (3) a 1.524-mm front gap thickness, a heat transfer coefficient of 5680 $W/m^2 \cdot °C$ is sufficient to remove the nuclear heat without exceeding the design temperature of 288°C.

2. A heater plate capacity of 5 kW is sufficient to supply the power necessary (~15 kW) to maintain the 288°C in the specimen assemblies in the absence of nuclear heating. The 30 kW available also assures that enough heat will be present in the event of heater failure without overloading the remaining heaters.

3. The gas-mixture conductivities have a wide range of control to adjust the level of temperatures with nuclear heating only. The heaters will be mainly used to reduce the thermal gradient within the required ±10°C.

The two capsules were installed in March 1980, and the experiment start-up was on April 30, 1980. The PVWS capsule is operating on a purge mixture of 0.75/0.25 neon/helium. The flat temperature distribution of 288°C ± 10°C is maintained by individually varying heater loads in the 30 heater regions. Table 11 presents an experimental temperature distribution obtained on August 7, 1980.

6. RECOMMENDATIONS

In the event that the LWR PV Benchmark Facility will continue to be used for similar experiments, recommendations are that testing and refining of the two models based on operating conditions should be carried out.

The design goal was achieved, and the flexibility built into the thermal control system proved capable of maintaining the design temperature at 288°C ± 10°C under the present range of operating conditions. However, a series of heating tests with electric heating only should be performed. By this method, uncertainties due to nuclear heating rates in the steel components may possibly be isolated from those due to modeling of the various parameters (geometric simulation and applied boundary conditions).

With improvement of the models, parameters may be chosen that will yield temperatures closer to design temperatures, with helium as sweep gas. As a result, the use of neon will be reduced, thus assuring a more economical mode of operation and better heater longevity with lower heater loads. Considering the duration of the experiment, these two improvements would result in a substantially more economical experiment with no loss of control.

Table 11. Operating temperature distribution of the PVWS capsule (August 7, 1980)

PVWS capsule recorded temperatures[a] (°C)					
Front face			Back face		
289[b]	290	289		290	
289[c]	290	291		290	
290[d]	288	290		288	
			291		*e*
			289		288
			287		286
288		289			
288		288			
288		288			
	e		292	292	293
	286		289	288	289
	286		292	286	292
285		286			
286		287			
288		289			
			289		288
			288		288
			288		287
282	292	283		*e*	
283	292	286		293	
e	291	289		289	

[a] Reference temperature 288; average temperatures 288.6, 288.3, and 288.5; maximum difference 6.0, 5.1, and 4.1 at specimen positions OT, 1/4T, and 1/2T, respectively.

[b] Specimen position OT.

[c] Specimen position 1/4T.

[d] Specimen position 1/2T.

[e] Unreliable thermocouple.

Appendix A

ISOTHERMS AND TEMPERATURE PROFILES FOR THE SSS AND PVWS CAPSULES

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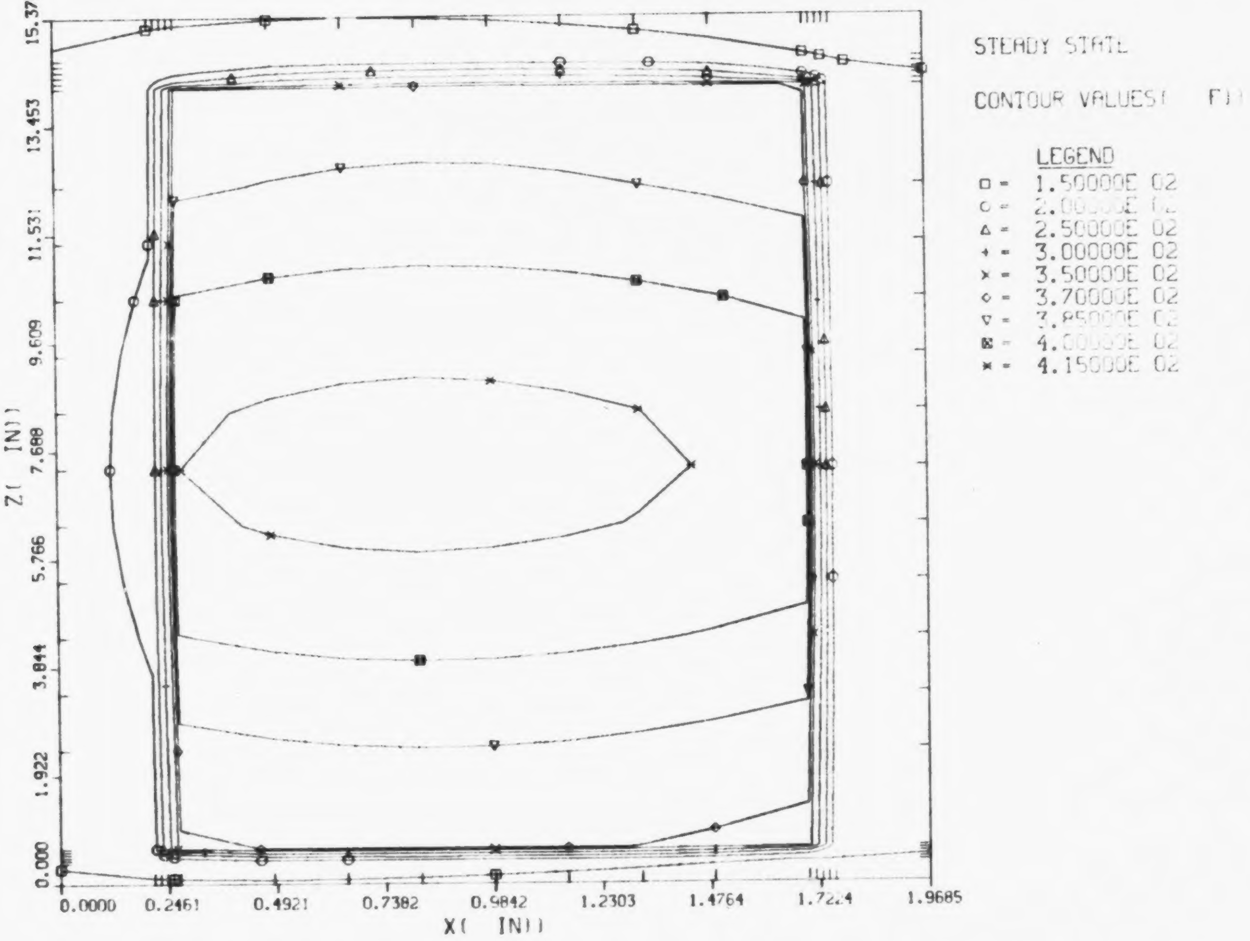

Fig. A.1. Isotherms in SSS capsule: front and back gap thicknesses — 0.035 in.

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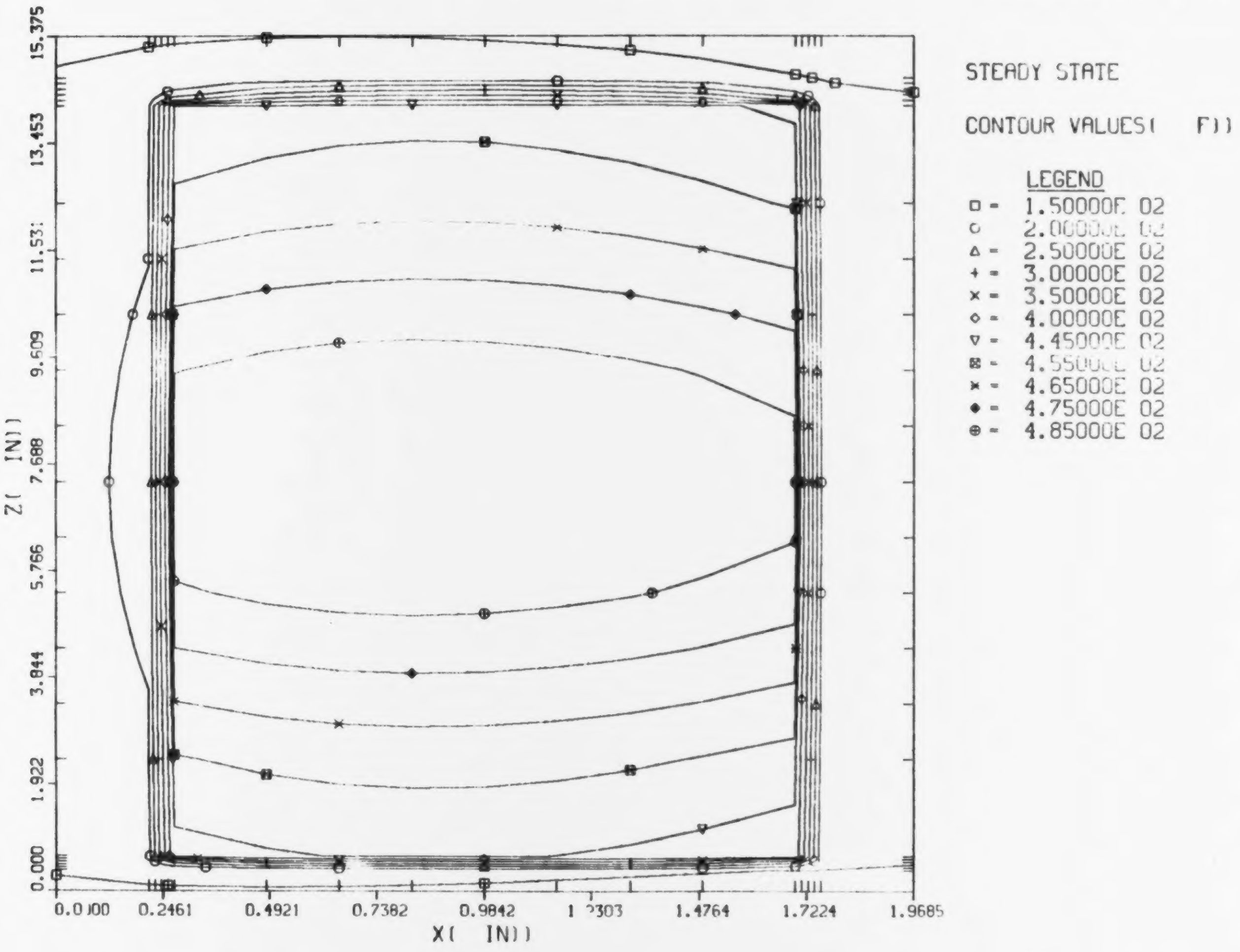

Fig. A.2. Isotherms in SSS capsule: front and back gap thicknesses — 0.050 in.

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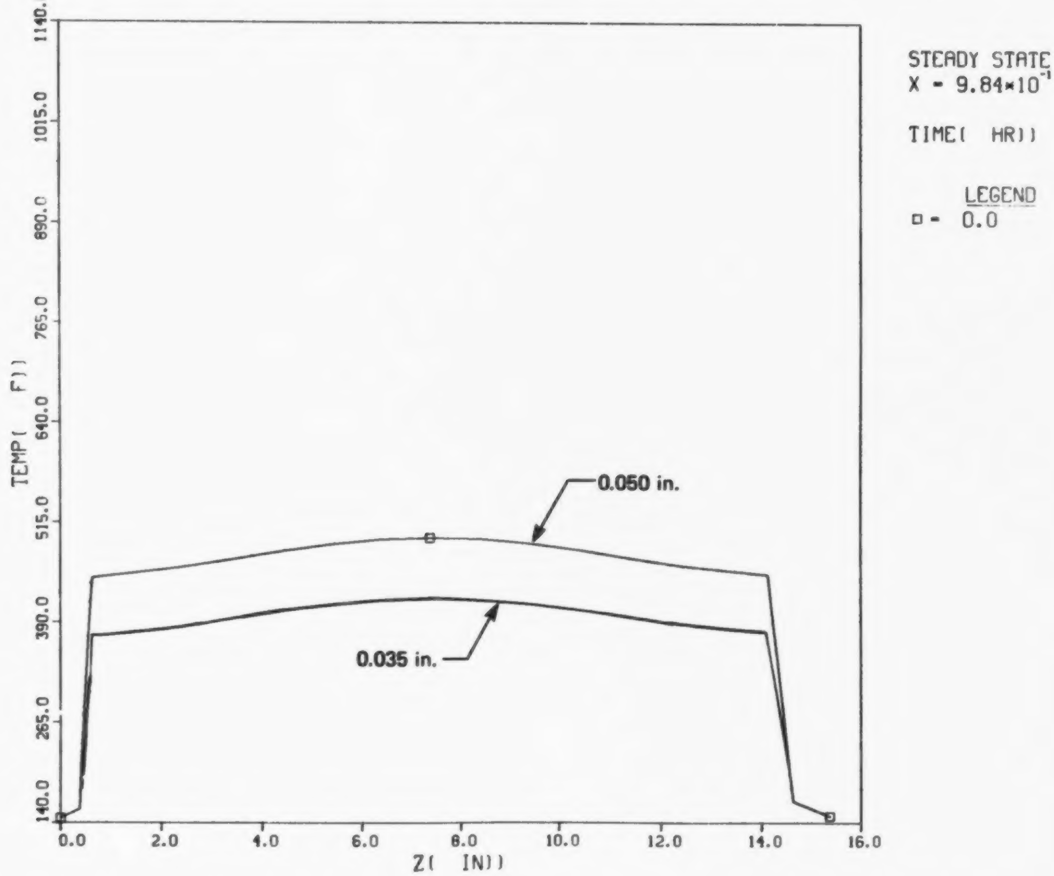

Fig. A.3. Vertical midplane profiles in SSS capsule resulting from gap thickness variation.

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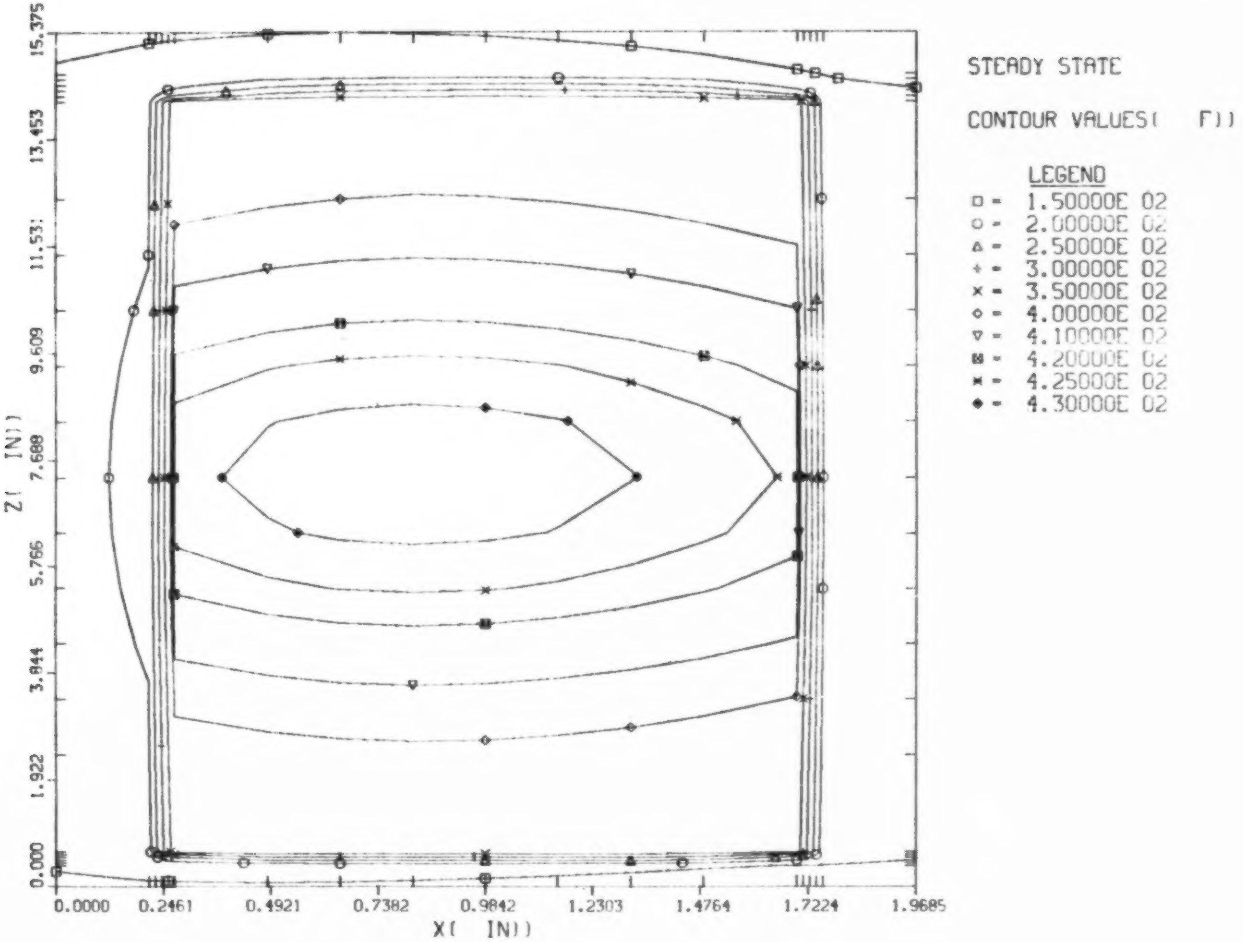

Fig. A.4. Isotherms in SSS capsule: gas conductivity variation — 9/1 helium/neon composition.

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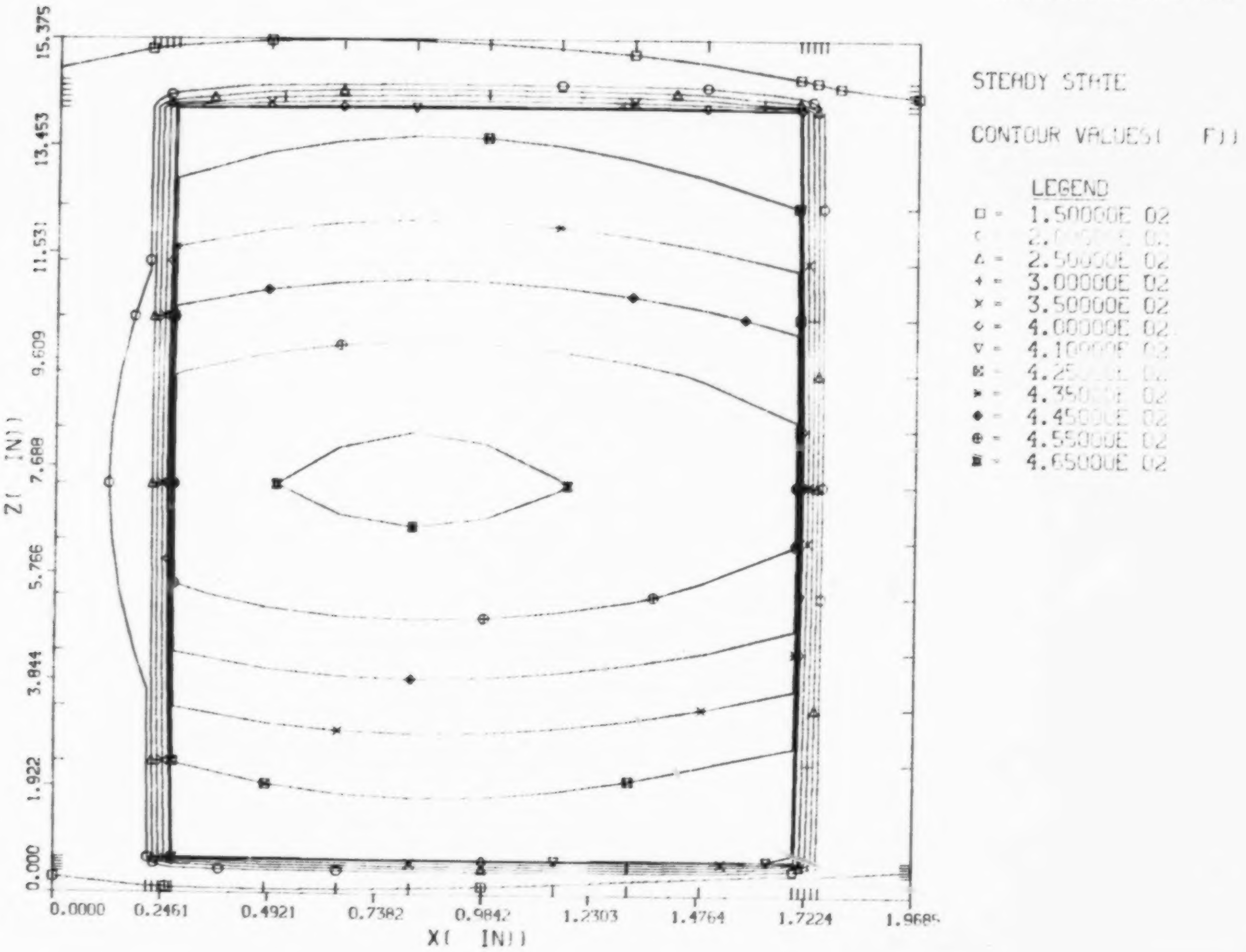

Fig. A.5. Isotherms in SSS capsule: gas conductivity variation — 7/3 helium/neon composition.

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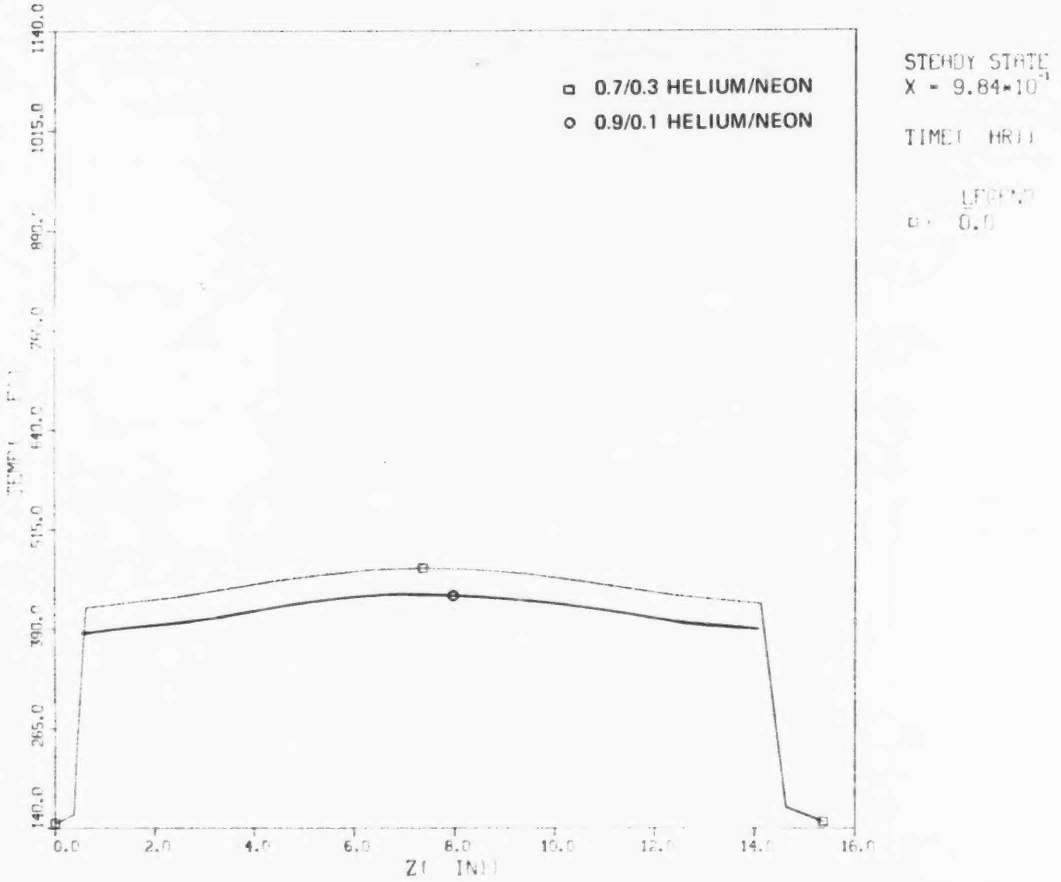

Fig. A.6. Vertical midplane profiles in SSS capsule resulting from gas mixture variation.

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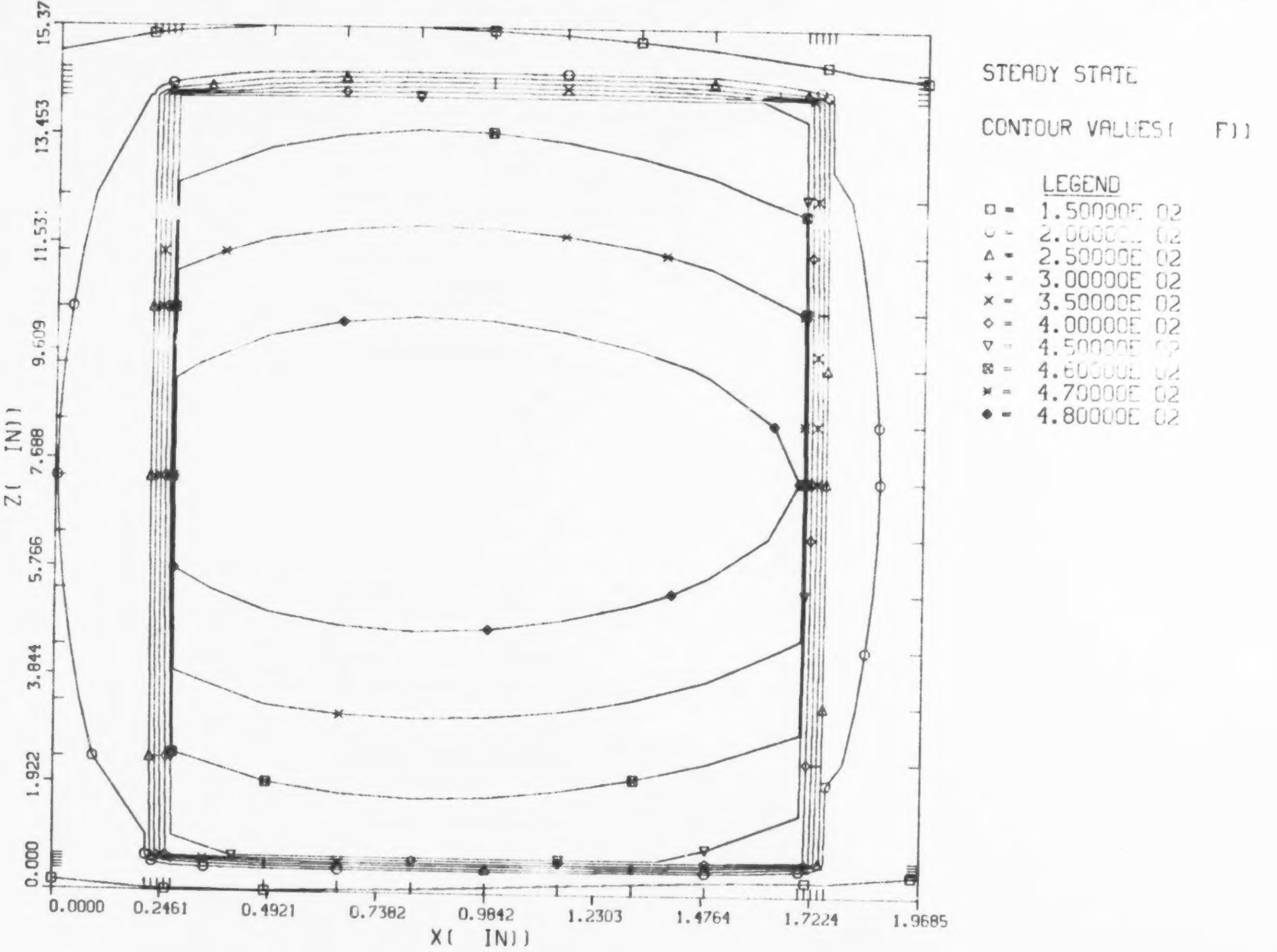

Fig. A.7. Isotherms in SSS capsule: electric heating at 1 kW/plate.

ORNL-DWG 81-7746 ETD

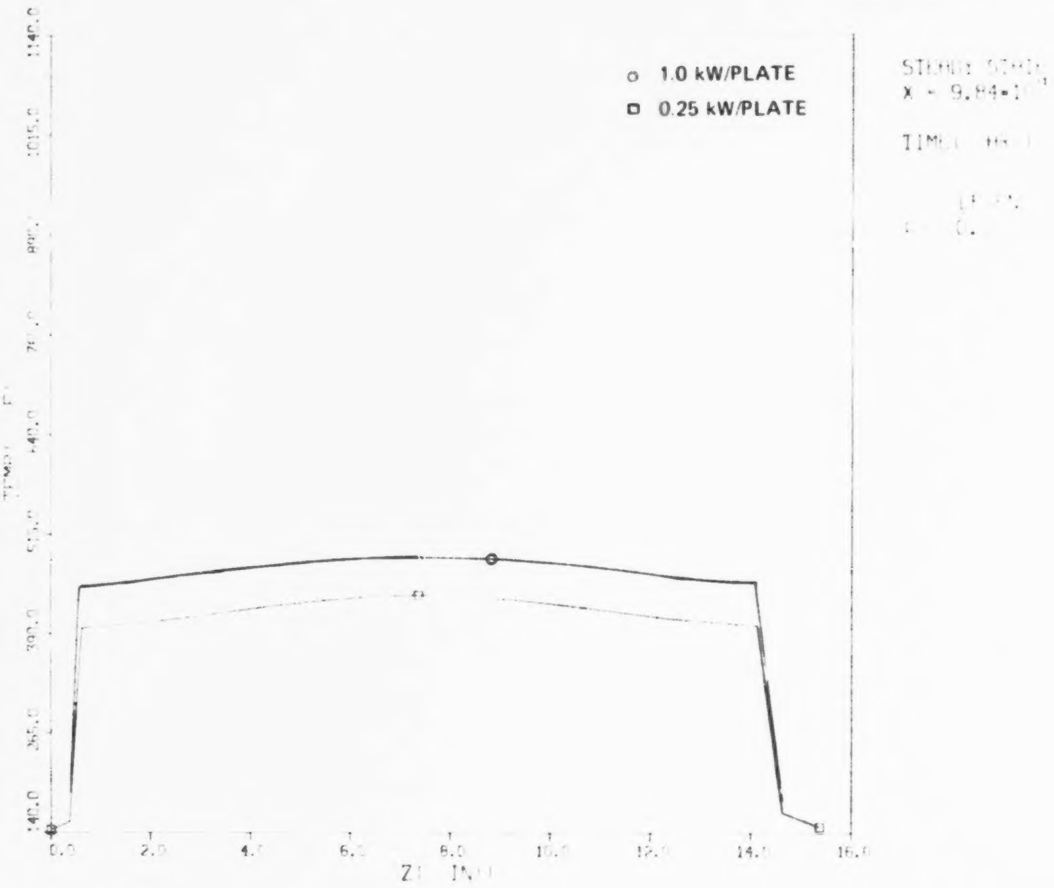

Fig. A.8. Vertical midplane profiles in SSS capsule resulting from electric power variation.

ORNL-DWG 81-7747 ETD

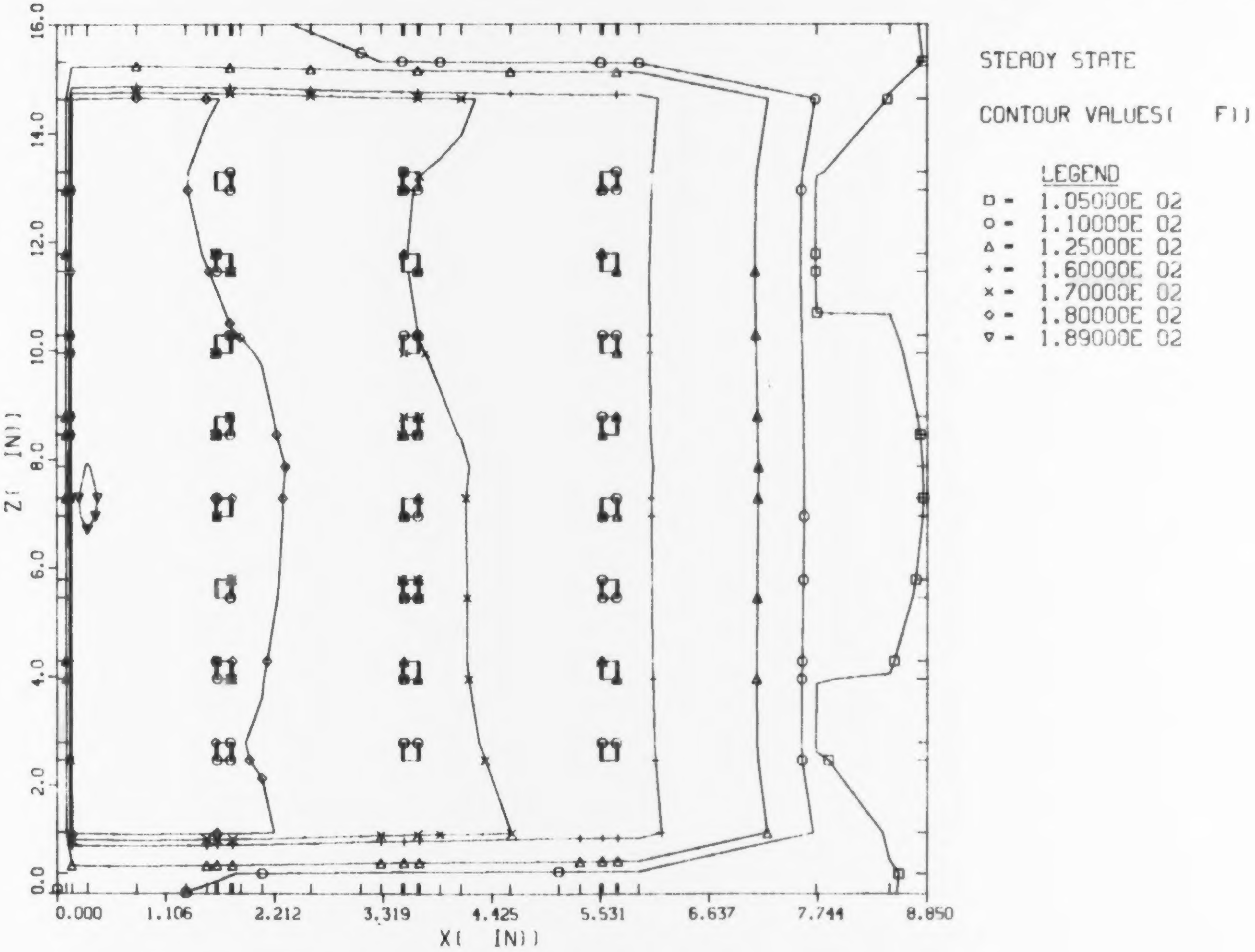

Fig. A.9. Isotherms in PVWS capsule: computed nuclear heating rate with helium sweep gas.

ORNL-DWG 81-7748 ETD

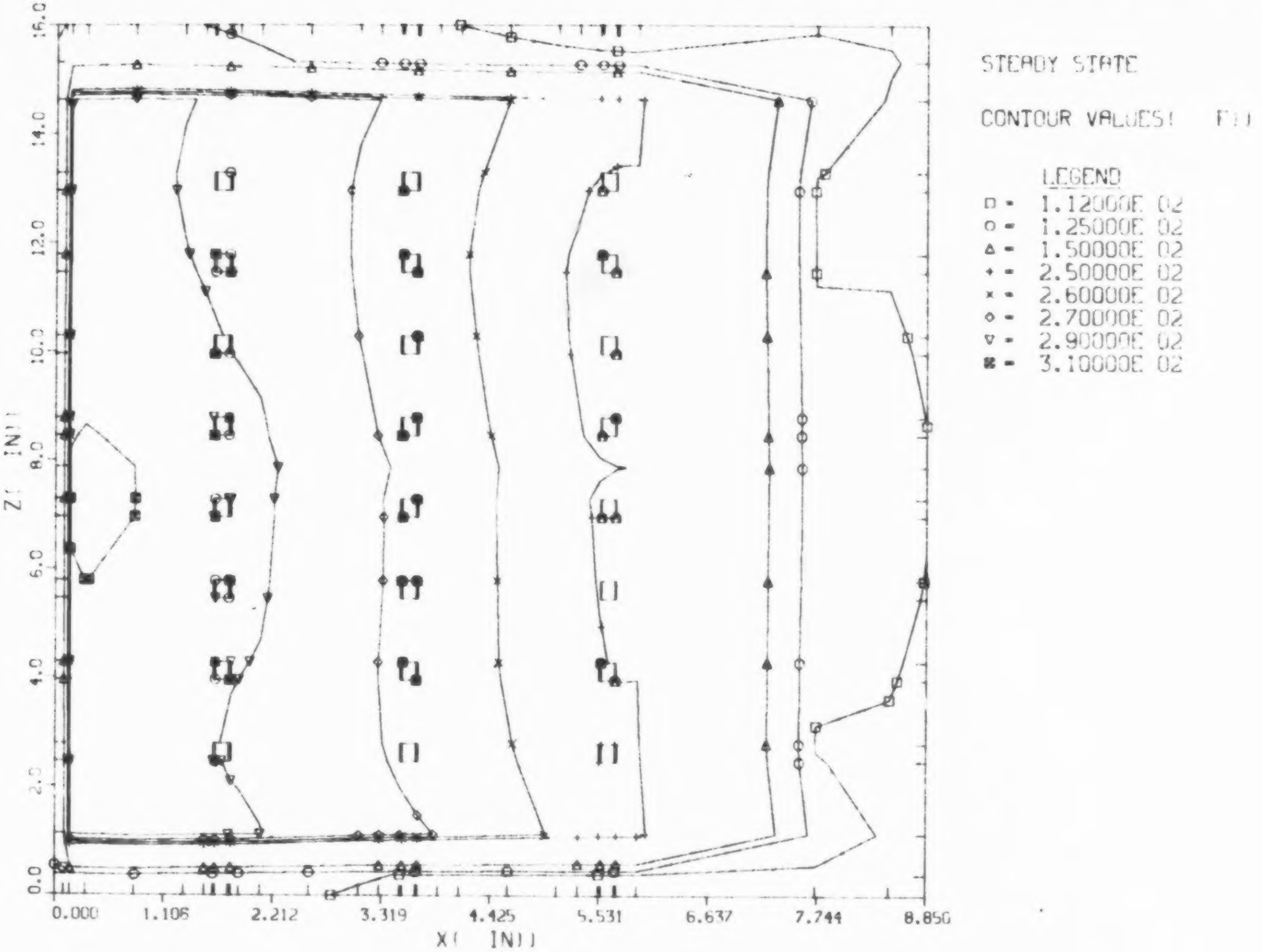

Fig. A.10. Isotherms in PVWS capsule: 2.5 × computed nuclear heating rate with helium sweep gas.

ORNL-DWG 81-7749 ETD

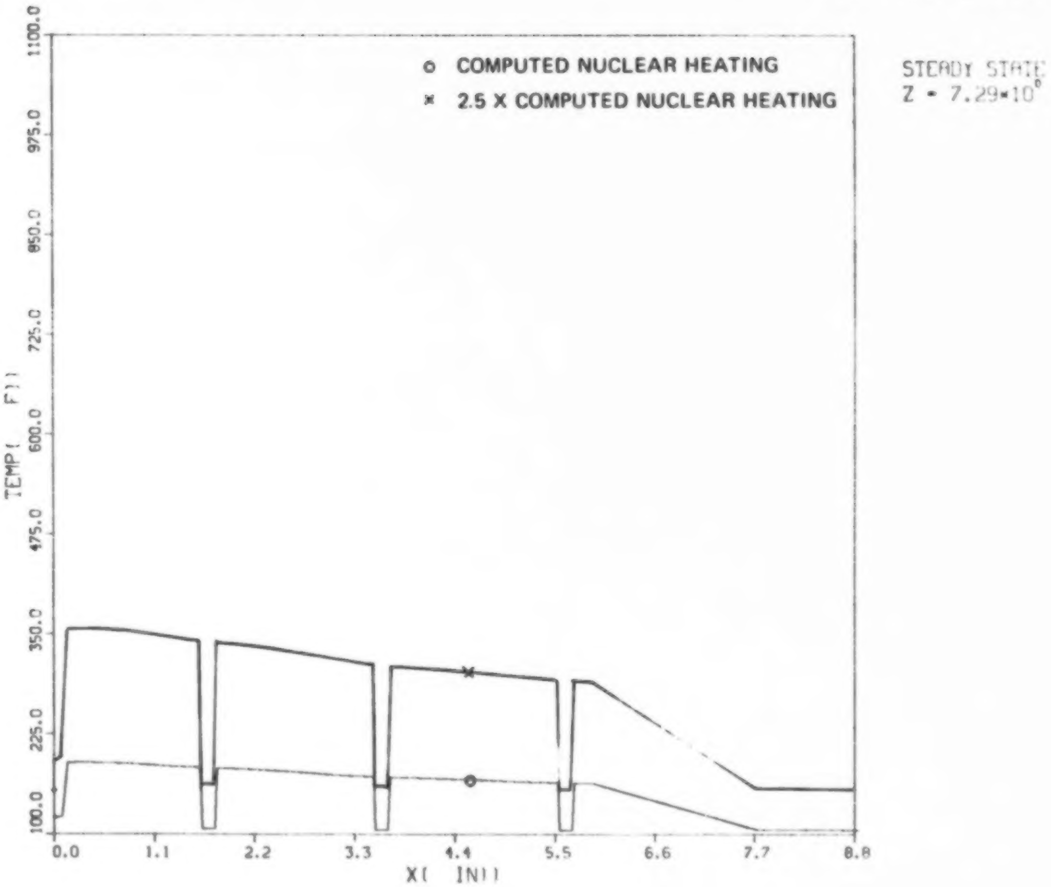

Fig. A.11. Horizontal profiles in PVWS capsule resulting from nuclear heating rate variation with helium.

ORNL-DWG 81-7750 ETD

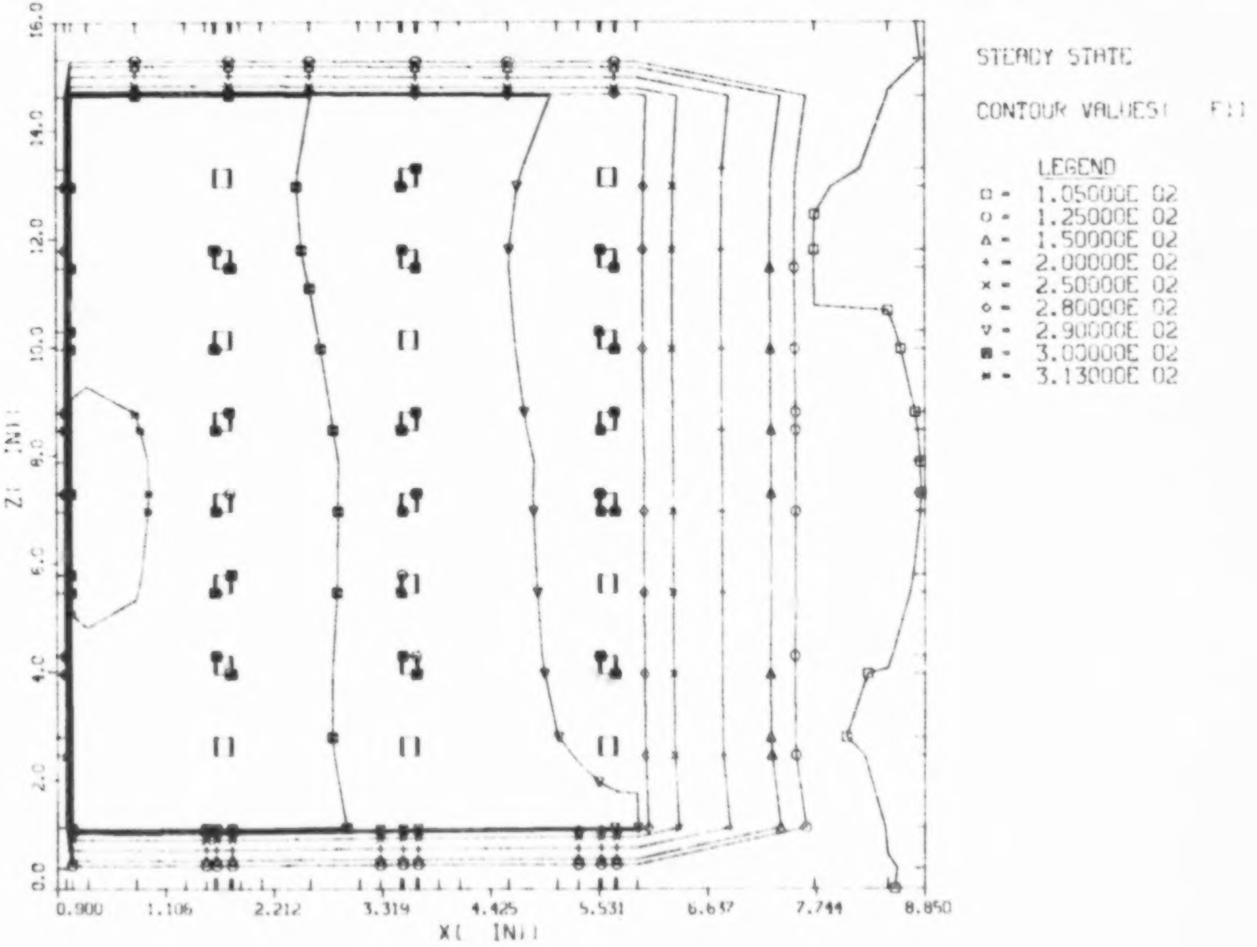

Fig. A.12. Isotherms in PVWS capsule: computed nuclear heating rate with neon sweep gas.

ORNL-DWG 81-7751 ETD

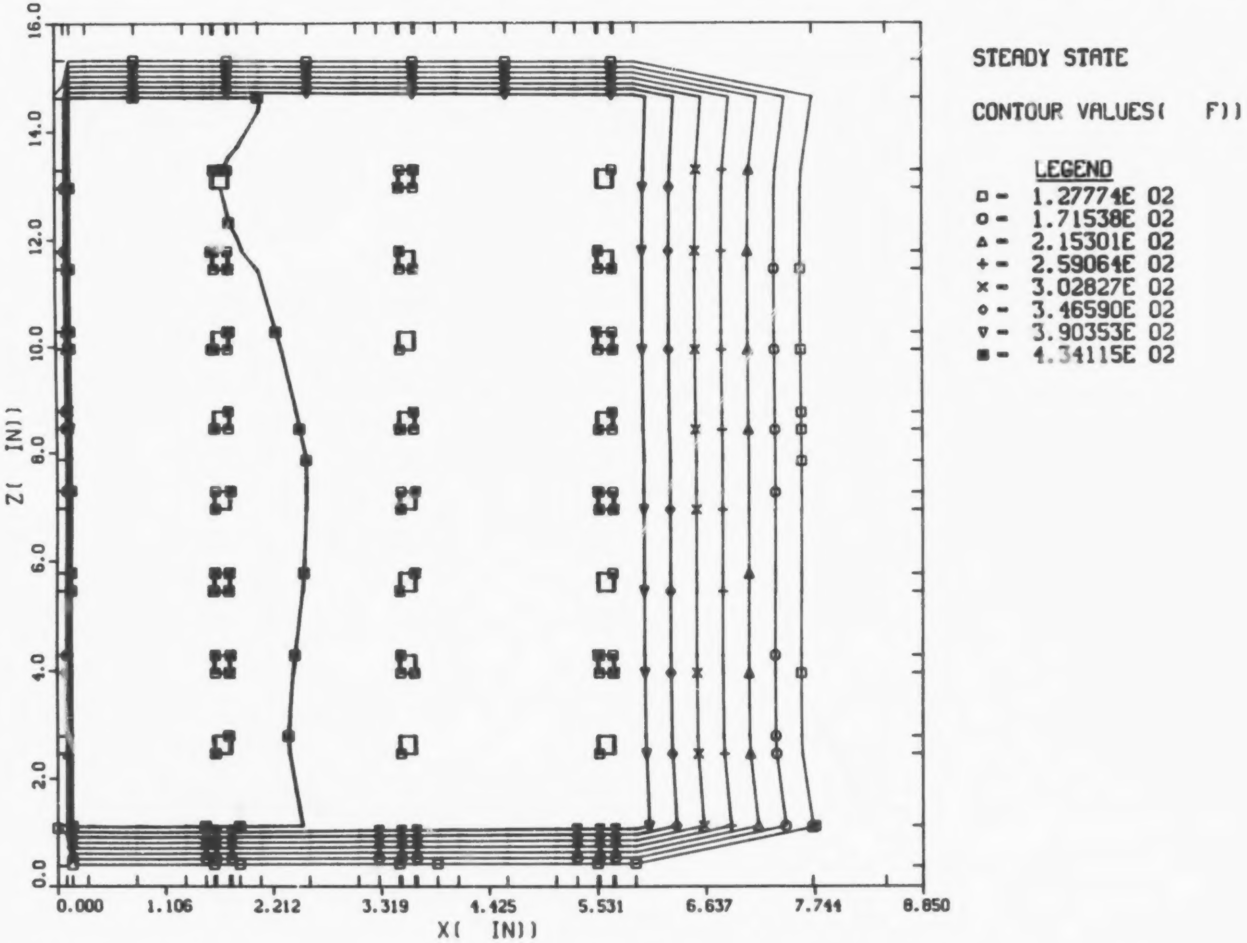

Fig. A.13. Isotherms in PVWS capsule: 1.75 × computed nuclear heating rate with neon sweep gas.

57

ORNL-DWG 81-7752 ETD

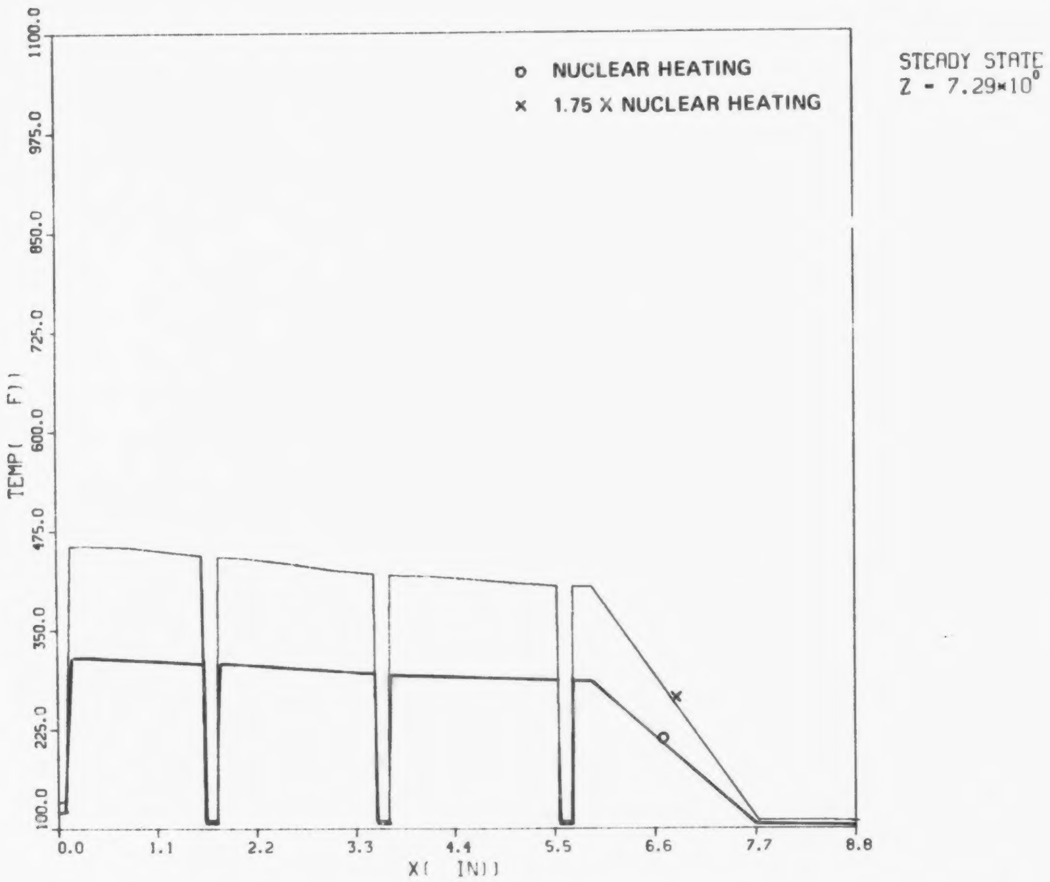

Fig. A.14. Horizontal profiles in PVWS capsule resulting from nuclear heating rate variation with neon.

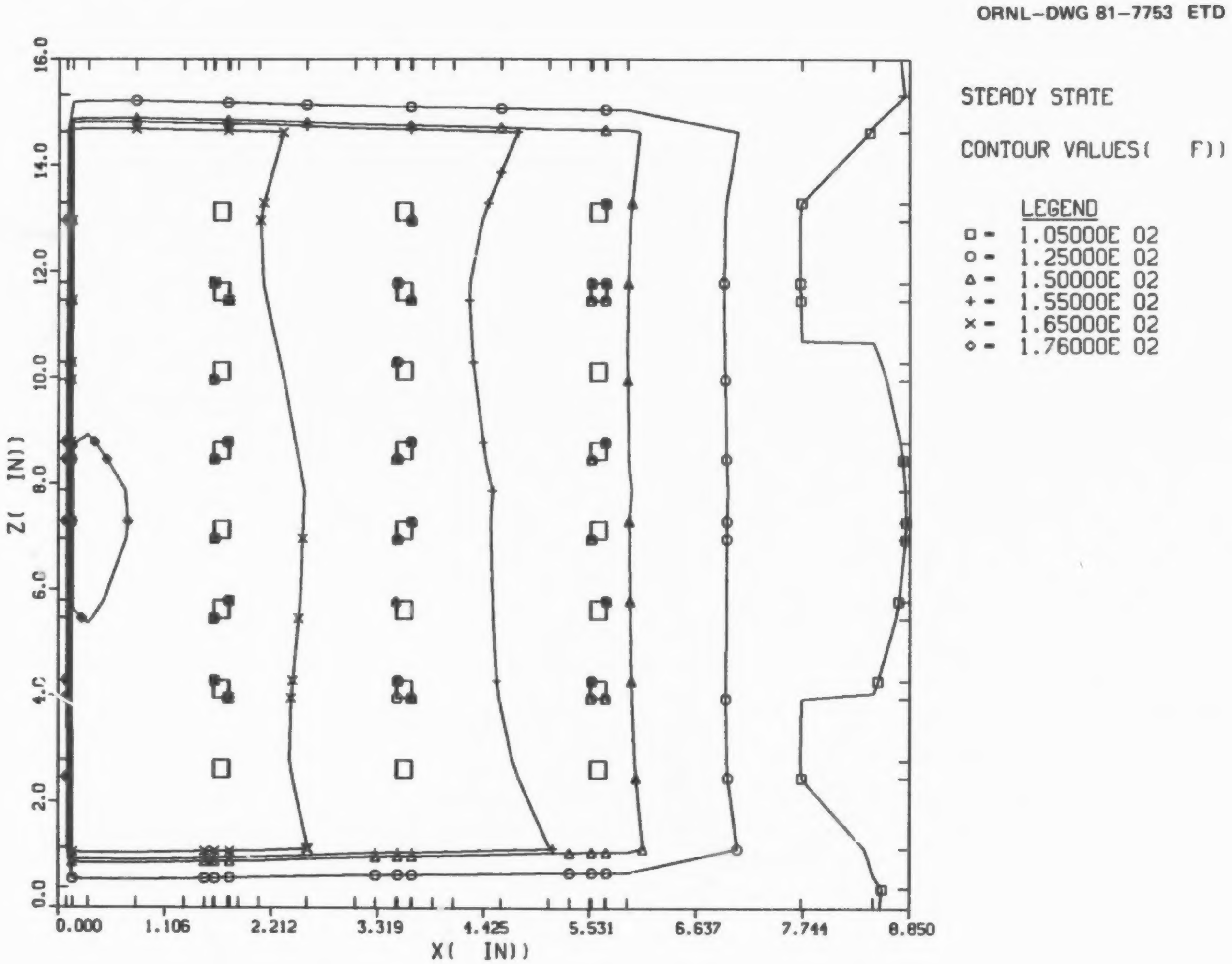

Fig. A.15. Isotherms in PVWS capsule: annular gap thickness — 0.015 in.

ORNL-DWG 81-7754 ETD

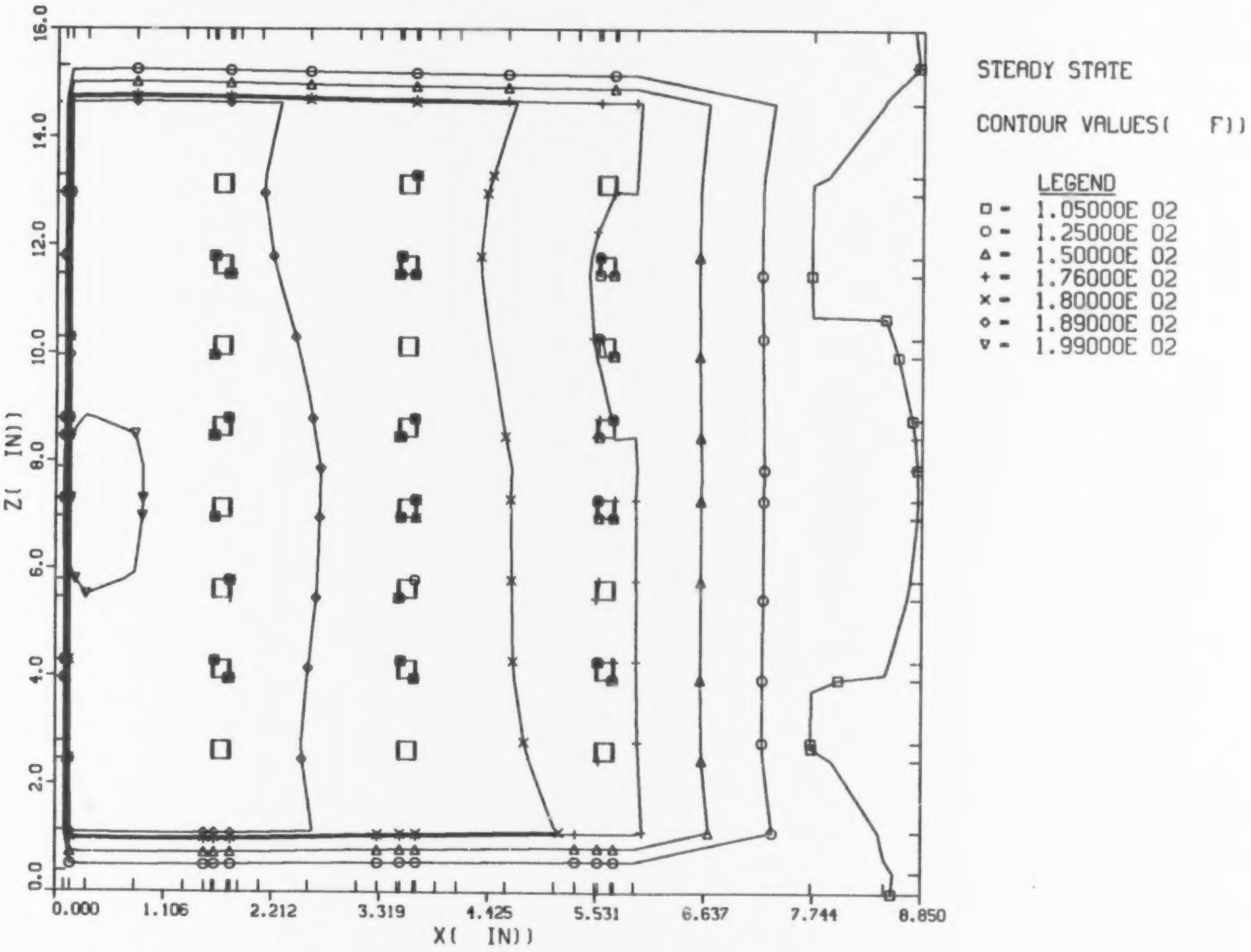

Fig. A.16. Isotherms in PVWS capsule: annular gap thickness — 0.025 in.

ORNL–DWG 81–7755 ETD

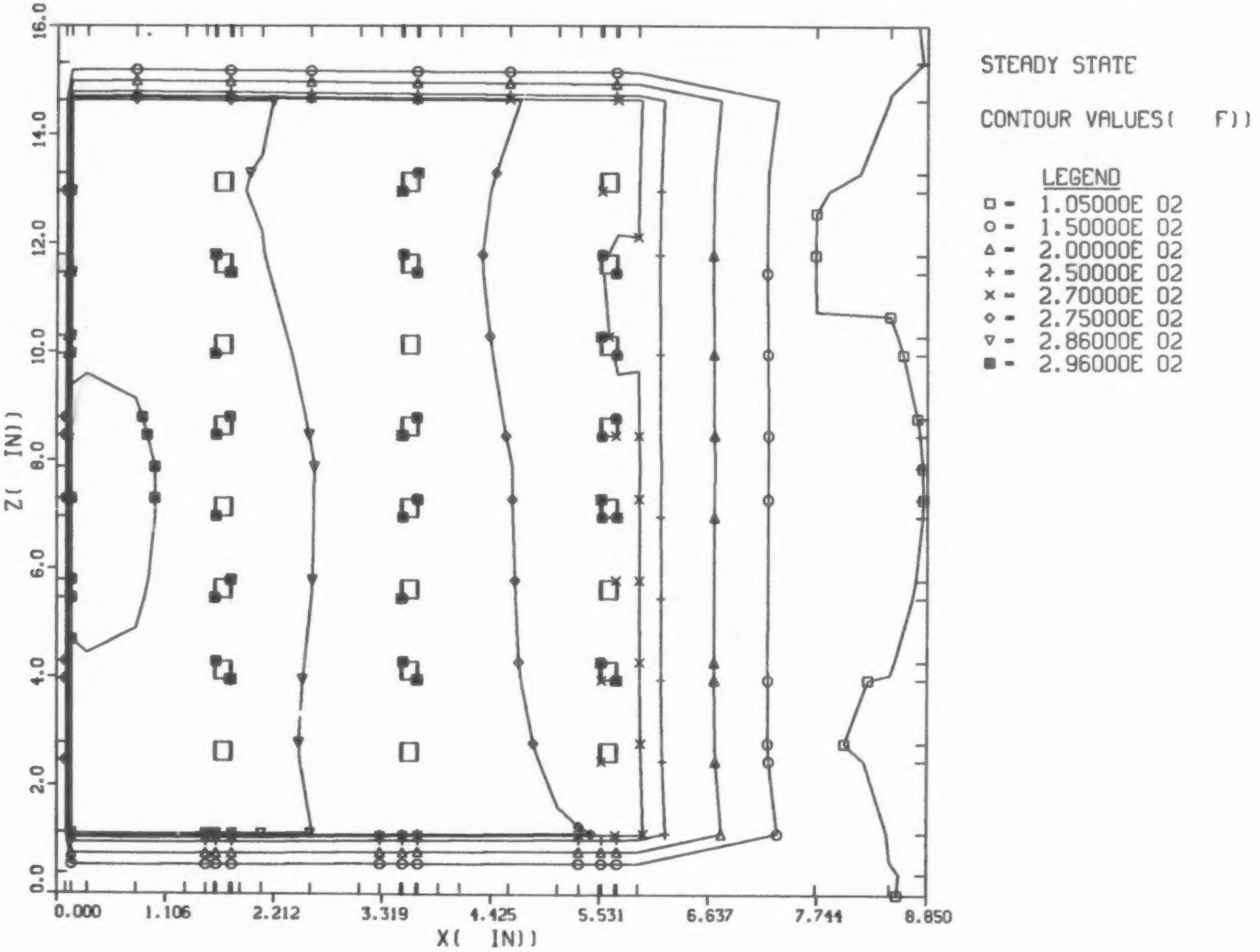

Fig. A.17. Isotherms in PVWS capsule: 1.1 × conductivity of neon.

ORNL-DWG 81-7756 ETD

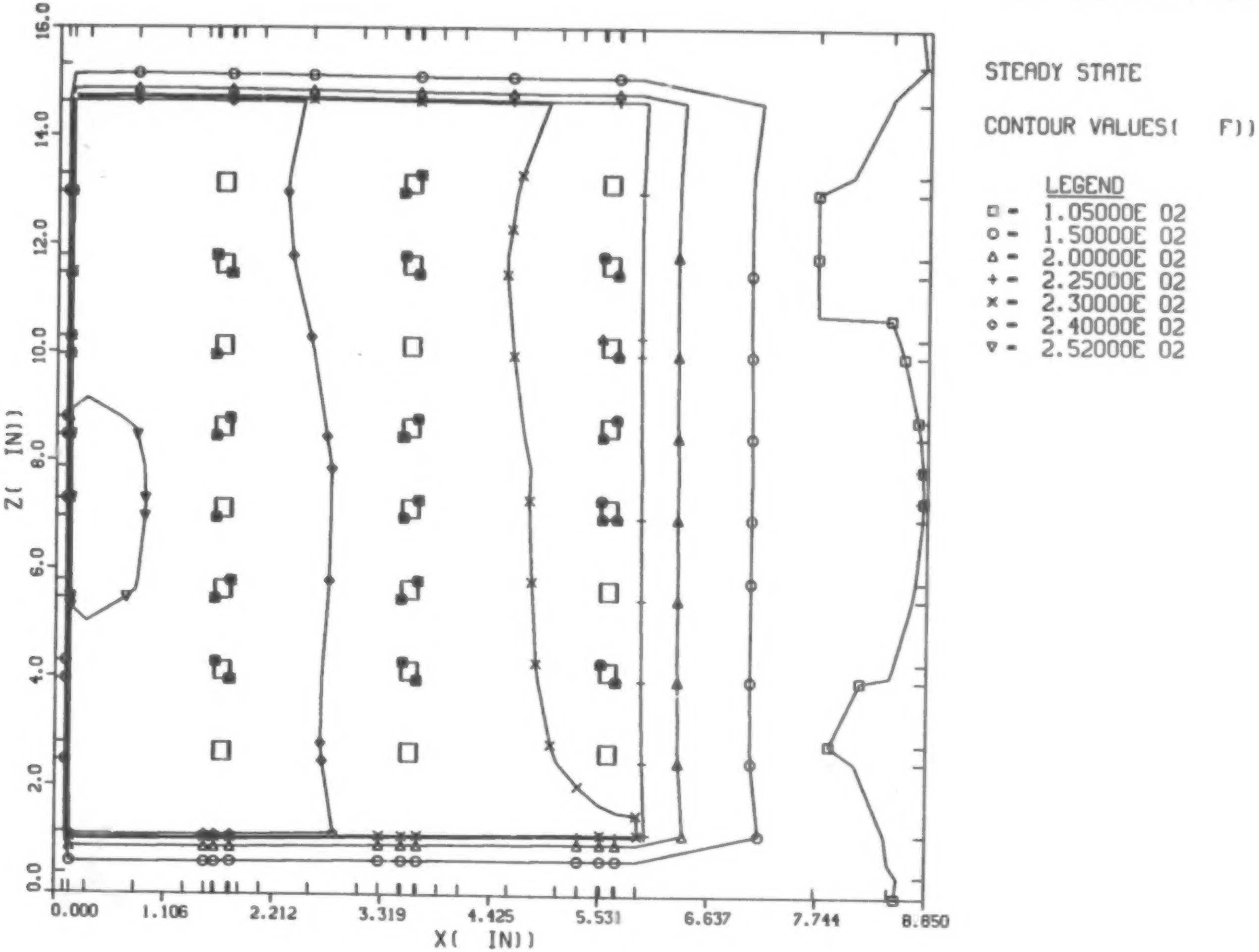

Fig. A.18. Isotherms in PVWS capsule: 1.5 × conductivity of neon.

ORNL-DWG 81-7757 ETD

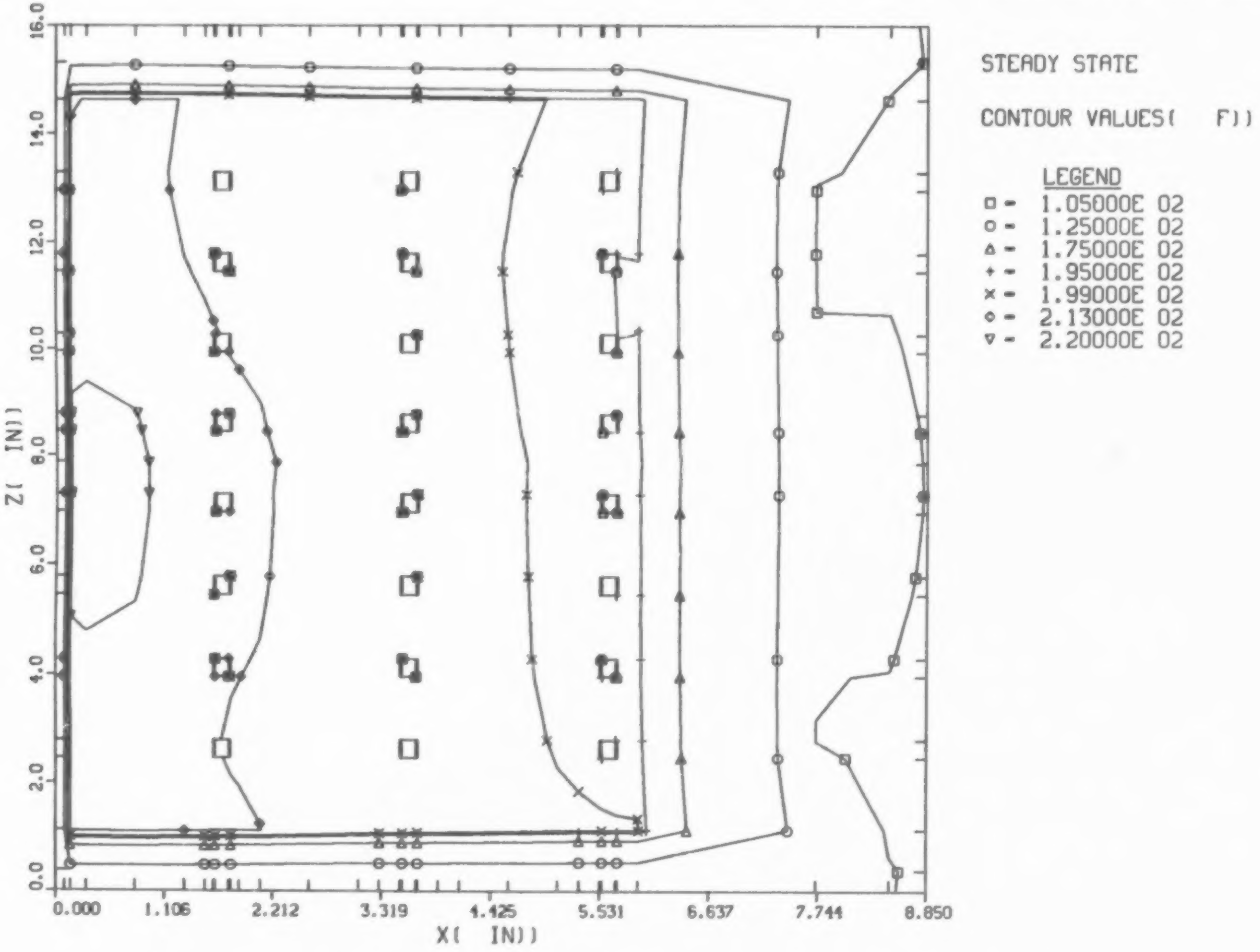

Fig. A.19. Isotherms in PVWS capsule: 2 × conductivity of neon.

ORNL-DWG 81-7758 ETD

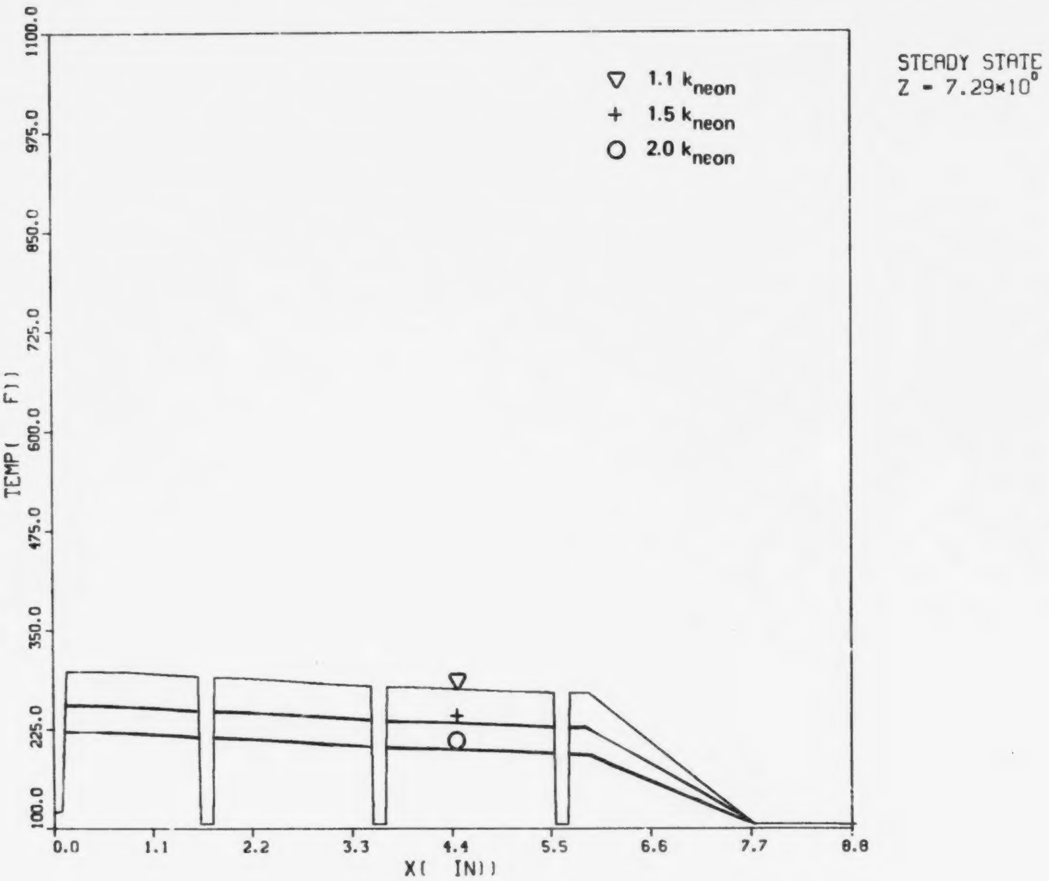

Fig. A.20. Horizontal profiles in PVWS capsule resulting from gas conductivity variation.

ORNL–DWG 81–7759 ETD

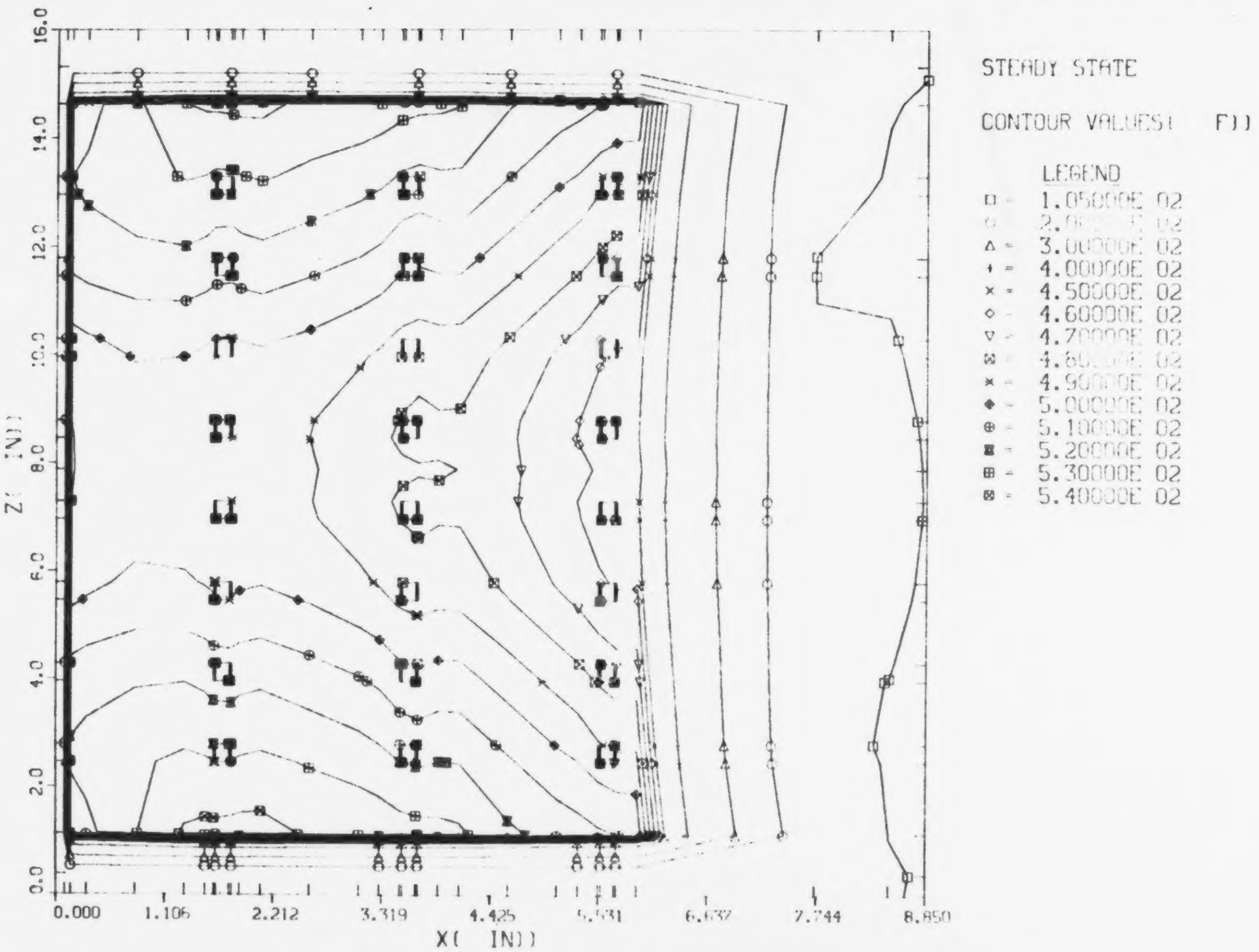

Fig. A.21. Isotherms in PVWS capsule: no nuclear heating with electric power of 2 kW/plate and helium.

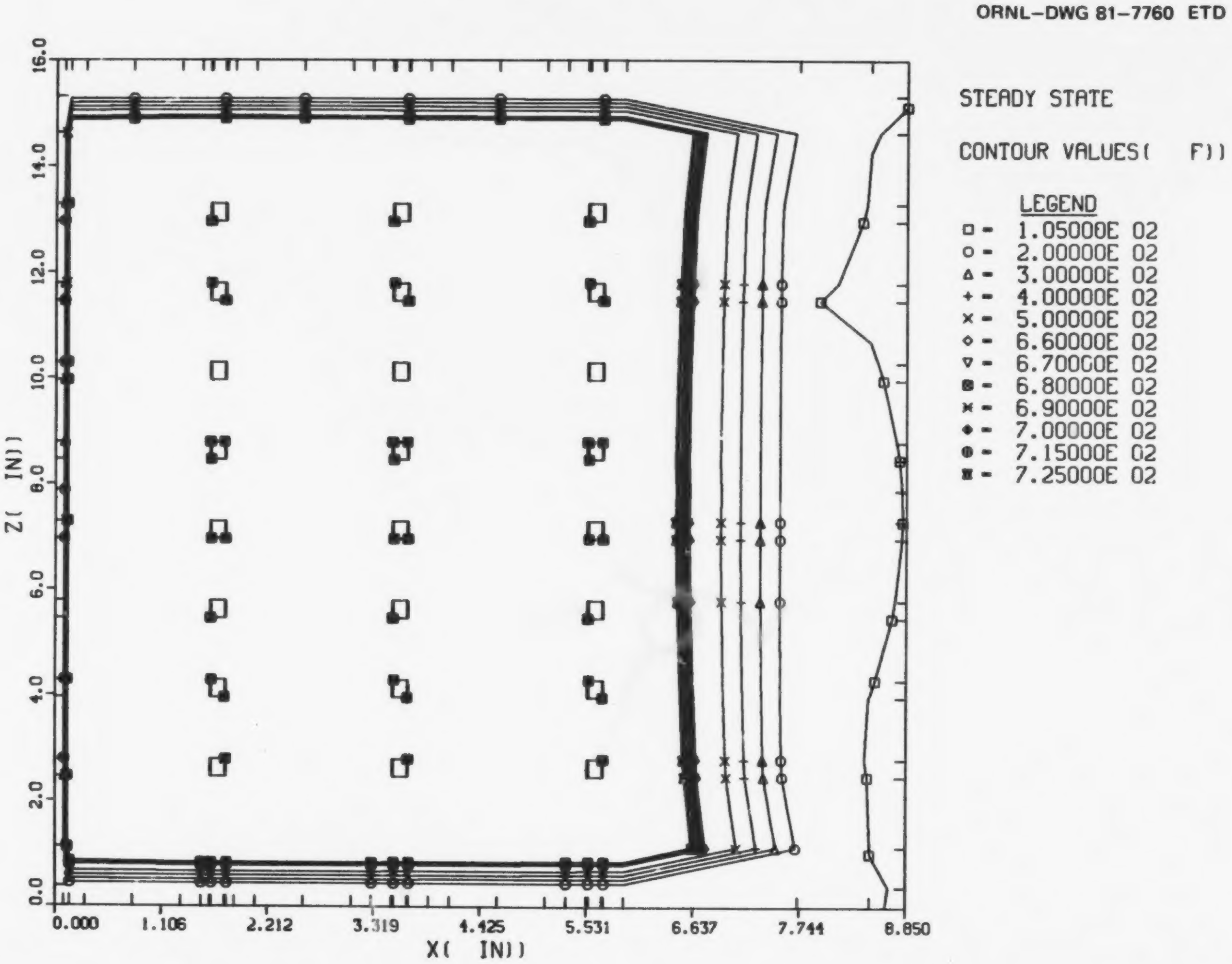

Fig. A.22. Isotherms in PVWS capsule: no nuclear heating with electric power of 2 kW/plate and neon.

ORNL-DWG 81-7761 ETD

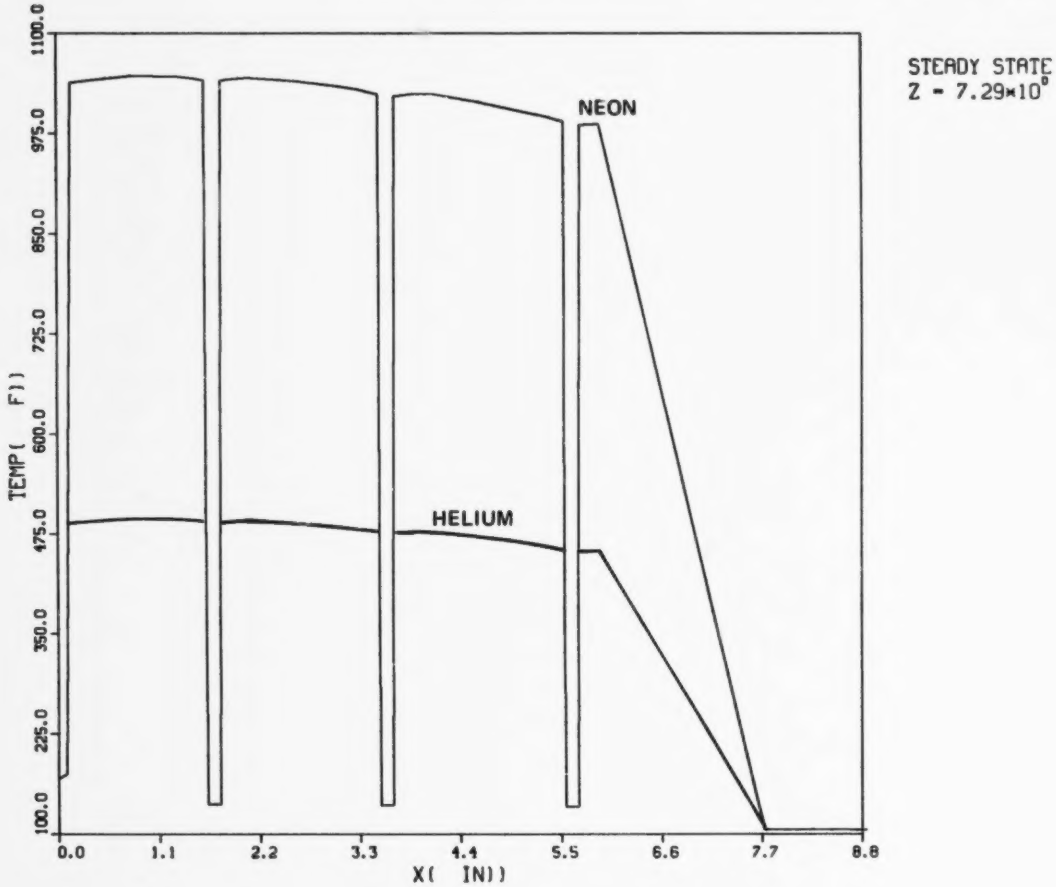

Fig. A.23. Horizontal profiles in PVWS capsule resulting from gas change with no nuclear heating and 2 kW/plate electric power.

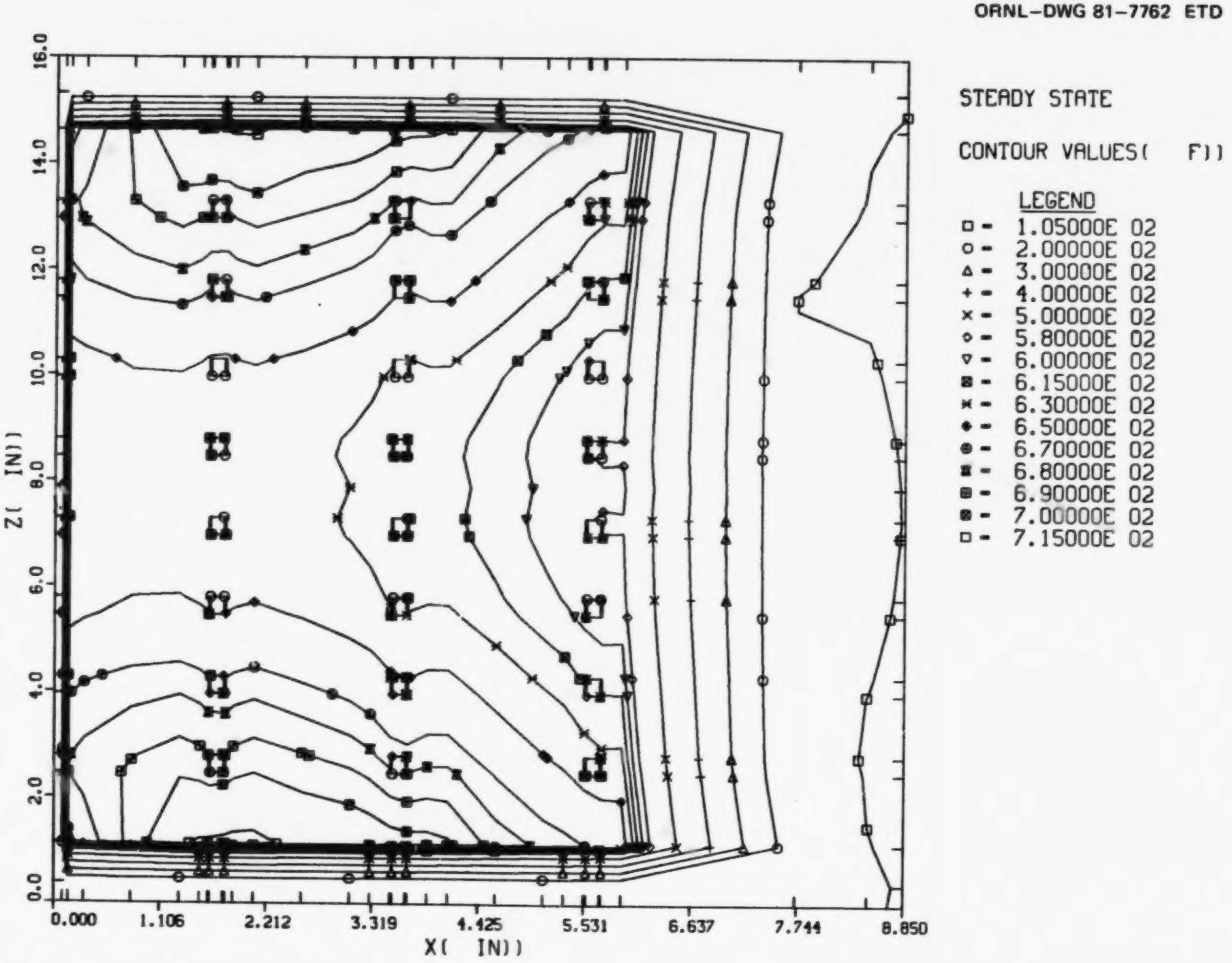

Fig. A.24. Isotherms in PVWS capsule: 3 kW/plate electric heating rate with computed nuclear heating (helium).

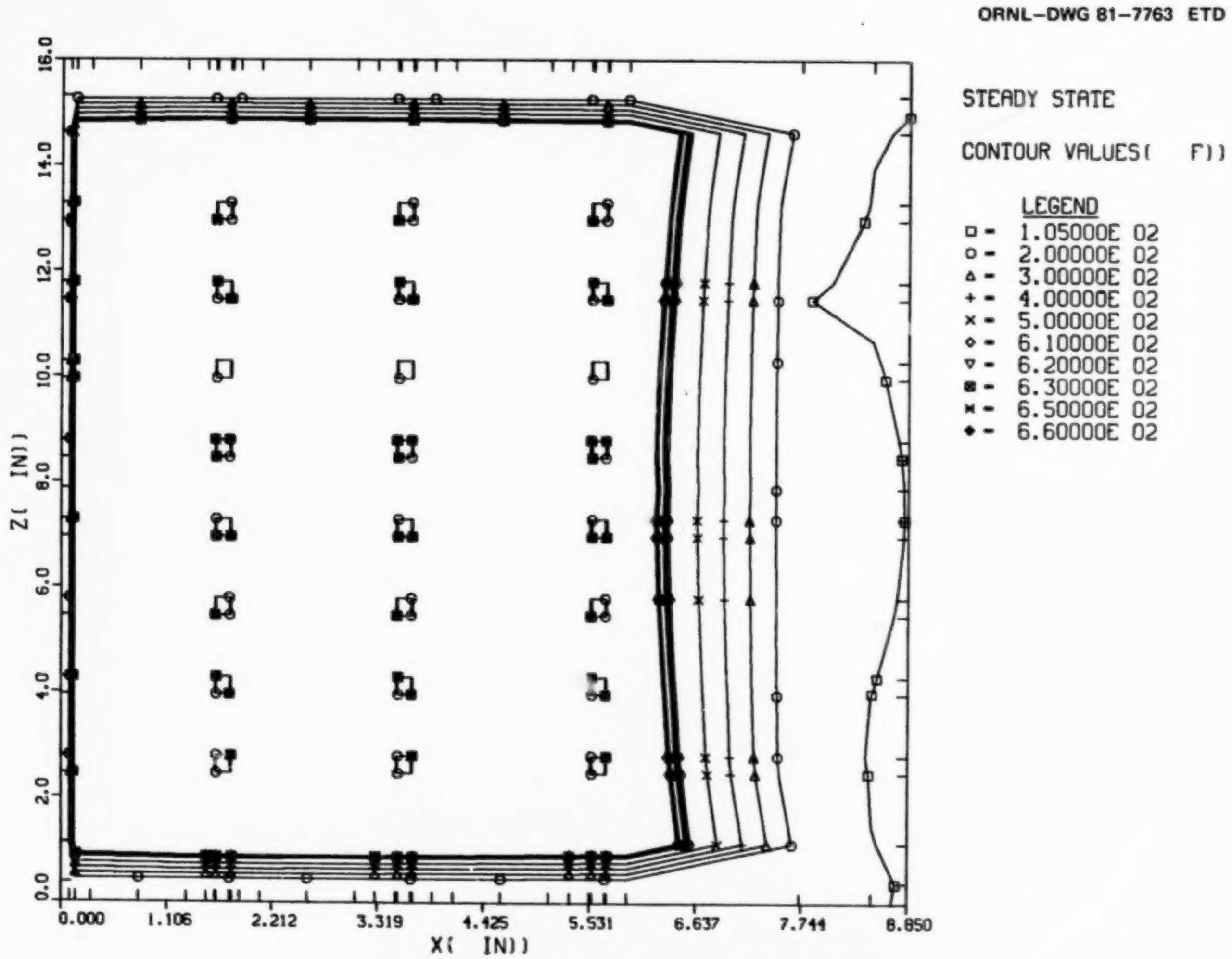

Fig. A.25. Isotherms in PVWS capsule: 3 kW/plate electric heating rate with computed nuclear heating (average helium/neon conductivity).

ORNL-DWG 81-7764 ETD

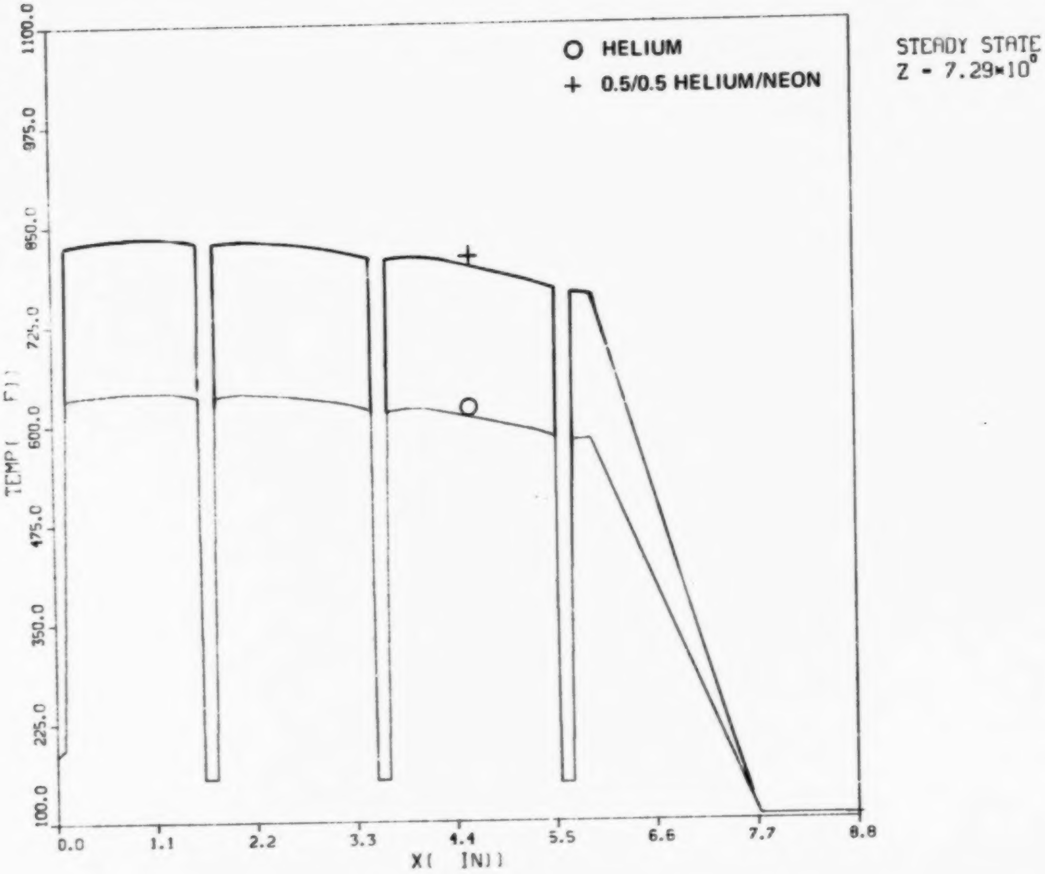

Fig. A.26. Horizontal profiles in PVWS capsule resulting from gas conductivity changes with 3 kW/plate electric power and nuclear heating.

ORNL-DWG 81-7765 ETD

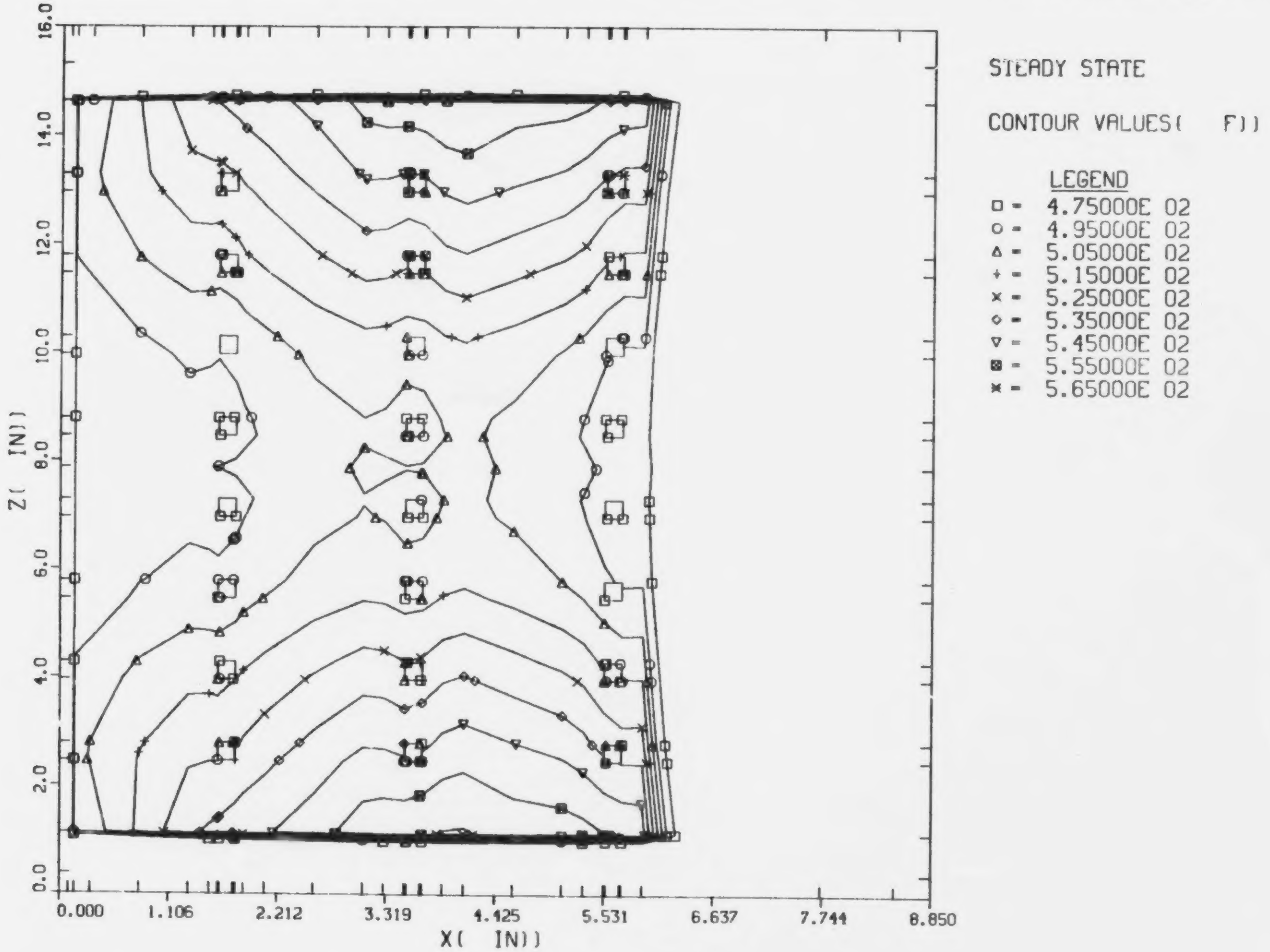

Fig. A.27. Isotherms in PVWS capsule: nonuniform heater loads — case 49.

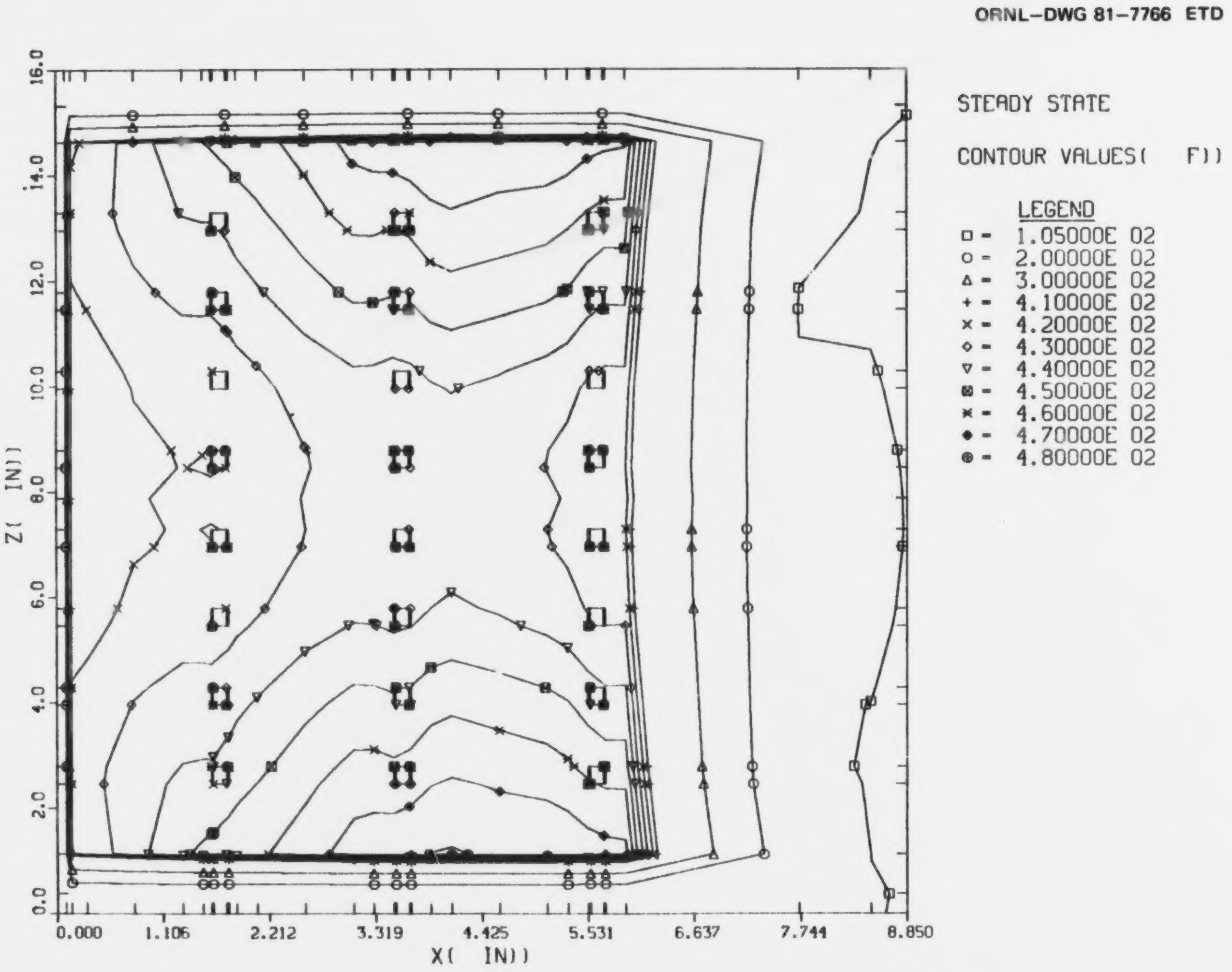

Fig. A.28. Isotherms in PVWS capsule: nonuniform heater loads — case 50.

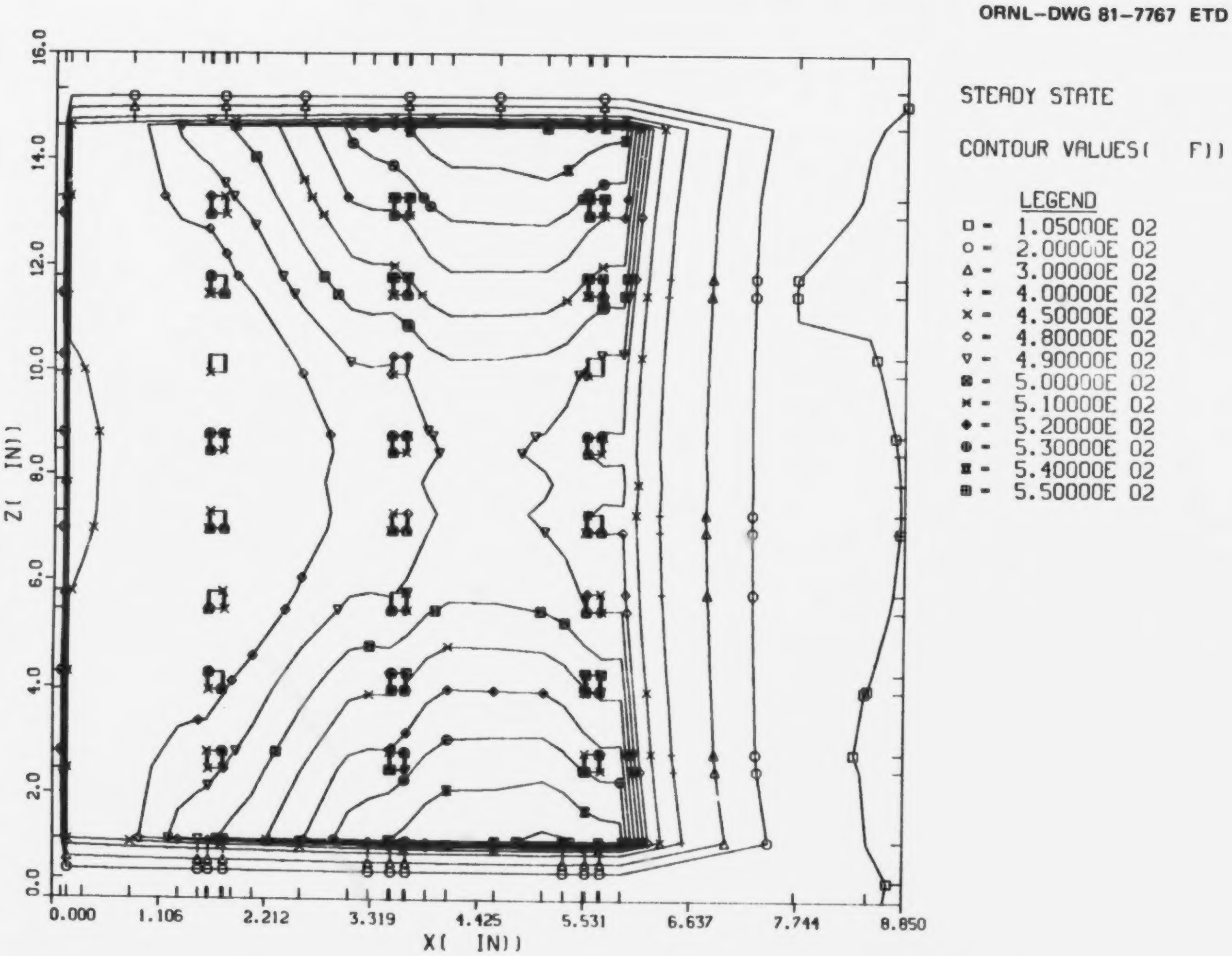

Fig. A.29. Isotherms in PVWS capsule: nonuniform heater loads — case 51.

ORNL-DWG 81-7768 ETD

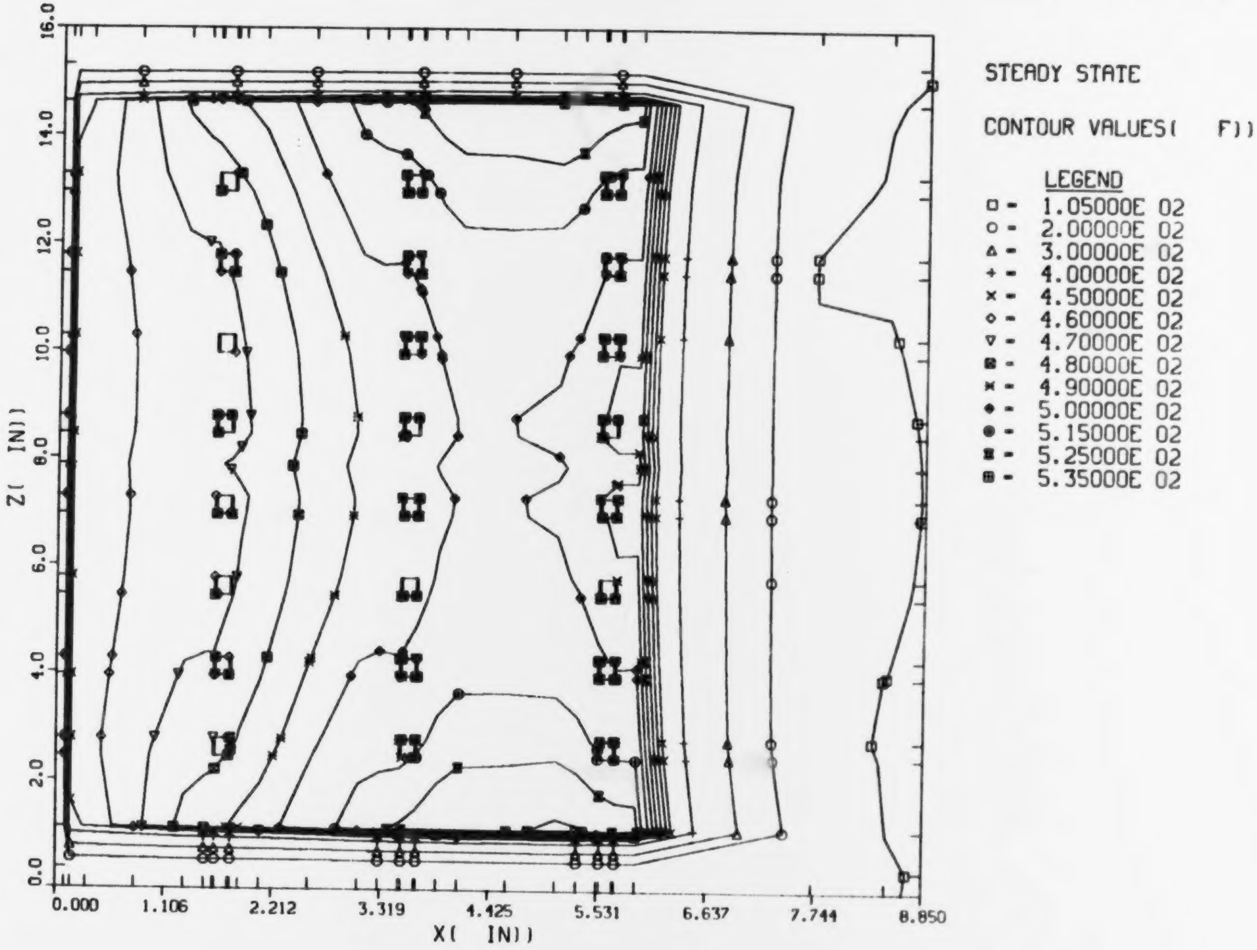

Fig. A.30. Isotherms in PVWS capsule: nonuniform heater loads — case 52.

ORNL-DWG 81-7769 ETD

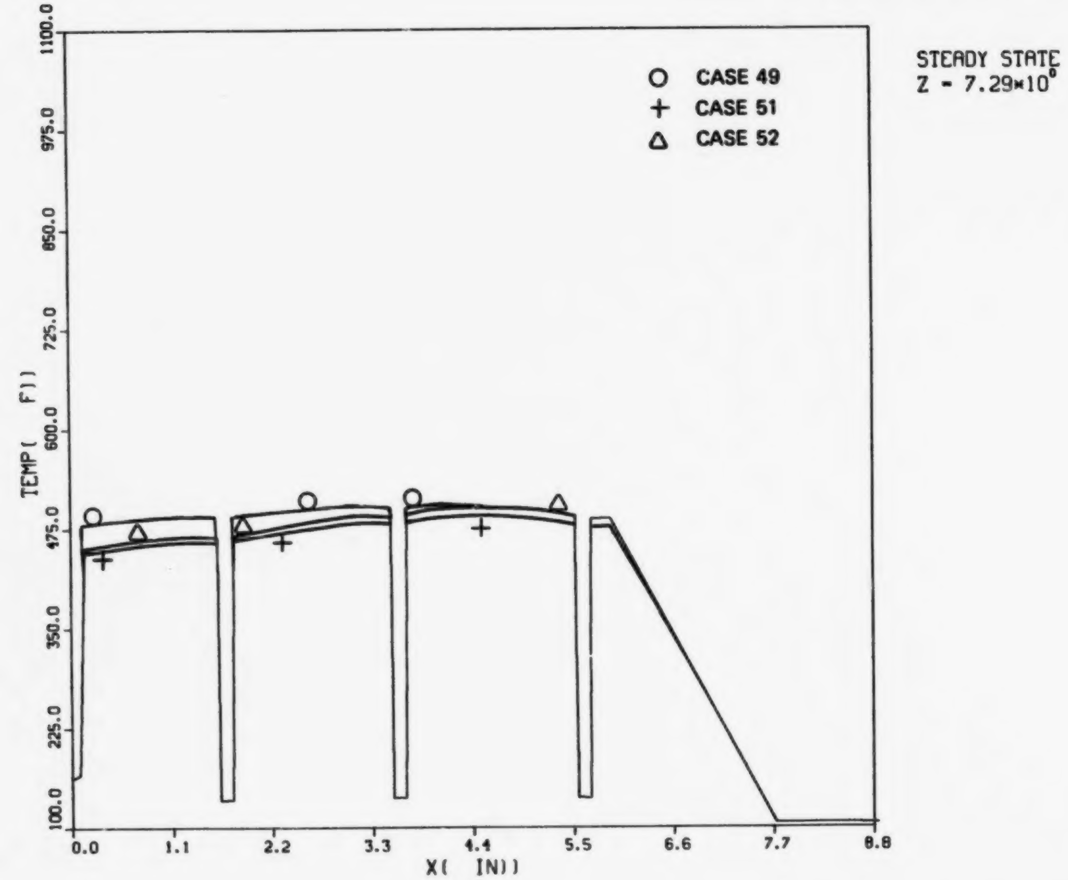

Fig. A.31. Horizontal profiles in PVWS capsule resulting from non-uniform heater loads in the three positions and varying distribution in heater plates.

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Appendix B

COMPUTER-RELATED MATERIAL: OUTPUT SAMPLES AND USER-SUPPLIED SUBROUTINES

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As a sample output for the SSS capsule model, this particular case has the following parameters:

1. computed nuclear heating rate modified by the Z-dependent factor,
2. a front and back gap thickness of 0.889 mm (0.035 in.),
3. helium sweep gas, and
4. no electric heat applied.

The units used in the computations are Btu, h, in., and °F.

```
HEATING5, A MULTI-DIMENSIONAL HEAT CONDUCTION CODE WITH TEMPERATURE-DEPENDENT THERMAL PROPERTIES,
NON-LINEAR AND SURFACE-TO-SURFACE BOUNDARY CONDITIONS AND CHANGE-OF-PHASE CAPABILITIES.
THIS VERSION OF THE CODE IS DESCRIBED IN ORNL/TM/CSD-15.
THE TRANSIENT SOLUTION CAN BE CALCULATED BY AN IMPLICIT TECHNIQUE (CRANK-NICOLSON OR
BACKWARDS EULER) FOR PROBLEMS WITH MATERIALS WHICH ARE NOT ALLOWED TO UNDERGO A PHASE CHANGE.
THE ONE-DIMENSIONAL R SPHERICAL MODEL WAS ADDED NOV. 75. THIS MODEL MAY BE ACCESSED
BY SPECIFYING NGEOM = 10 IN THE INPUT DATA.
HEATING5 WAS WRITTEN BY

     W.D. TURNER
     D.C. ELROD
     I.I. SIMAN-TOV
     COMPUTER SCIENCES DIVISION
     UNION CARBIDE CORPORATION, NUCLEAR DIVISION
             OAK RIDGE, TENNESSEE 37830

THIS VERSION OF HEATING CAN HANDLE A MAXIMUM OF    500 LATTICE POINTS.

INPUT RETURN

  DATE 11-30-80
  TIME 09.40.59

  JOB DESCRIPTION-- SURVEILLANCE SPECIMEN SIMULATOR
  THE PROBLEM WILL BE TERMINATED AFTER       120 SECONDS
  GEOMETRY TYPE NUMBER     8 (OR XZ  )
  NUMBER OF REGIONS     13
  NUMBER OF MATERIALS      6
  NUMBER OF HEAT GENERATION FUNCTIONS     3
  NUMBER OF INITIAL TEMPERATURE FUNCTIONS      1
  NUMBER OF DIFFERENT KINDS OF BOUNDARIES     4
  THIS PROBLEM INVOLVES TEMPERATURE-DEPENDENT PROPERTIES.
  NUMBER OF POINTS IN GROSS X OR R LATTICE     9
  NUMBER OF POINTS IN GROSS Y OR THETA LATTICE     0
  NUMBER OF POINTS IN GROSS Z LATTICE     9
  NUMBER OF ANALYTIC FUNCTIONS    2
  NUMBER OF TABULAR FUNCTIONS   13
  A DATA SET TO BE USED TO CREATE GRAPHICAL OUTPUT OF
  THE TEMPERATURE DISTRIBUTION WILL BE STORED ON UNIT 31
  THE FINAL TEMPERATURE DISTRIBUTION WILL BE WRITTEN ON UNIT     32 IN FORMATTED FORM
  PROBLEM TYPE NUMBER     1
  STEADY STATE CONVERGENCE CRITERION  1.0000000D-07
  MAXIMUM NUMBER OF STEADY-STATE ITERATIONS    -50
  NUMBER OF ITERATIONS BETWEEN TEMPERATURE DEPENDENT
  PARAMETER EVALUATIONS FOR STEADY STATE CALCULATIONS      0
  INITIAL OVERRELAXATION FACTOR (BETA) FOR STEADY STATE CALCULATIONS  1.9000000
  INITIAL TIME  0.0
```

```
                                                                        SUMMARY OF REGION DATA
NUMBERS AND FCN NUMBER   ******************************* DIMENSIONS *******************************   -------- BOUNDARY NUMBERS --------
REG.  MATL  INIT  HEAT   LEFT-X-OR   RIGHT-X-OR   LOWER-Y-OR   UPPER-Y-OR     REAR-Z      FRONT-Z     LF-X  RT-X  LO-Y  UP-Y  RR-Z  FT-Z
 NO.   NC.  TEMP  GEN.    INNER-R     CUTER-R     LEFT-THETA  RIGHT-THETA                             IN-R  OT-R  LF-O  RT-O
   1     1     1     1    0.0          0.2123        0.0          0.0          0.0         15.3750       1     C     0     0     2     3
   2     1     1     1    0.2123       1.7563        0.0          0.0          0.0          0.3750       0     0     0     0     2     0
   3     1     1     1    0.2123       1.7563        0.0          0.0         14.6250      15.3750       0     0     0     0     0     3
   4     1     1     1    1.7563       1.9685        0.0          0.0          0.0         15.3750       0     4     0     0     2     3
   5     6     1     0    0.2123       0.2723        0.0          0.0          0.3750      14.6250       0     C     0     0     0     0
   6     2     1     0    0.2723       1.6963        0.0          0.0          0.3750       0.6250       0     C     0     0     0     0
   7     2     1     0    0.2723       1.6963        0.0          0.0         14.1250      14.6250       0     C     0     0     0     0
   8     6     1     0    1.6963       1.7563        0.0          0.0          0.3750      14.6250       0     C     0     0     0     0
   9     3     1     1    0.2723       0.4843        0.0          0.0          0.6250      14.1250       0     C     0     0     0     0
  10     3     1     1    1.4843       1.6963        0.0          0.0          0.6250      14.1250       0     C     0     0     0     0
  11     4     1     1    0.4843       1.4843        0.0          0.0          0.6250       2.3750       0     C     0     0     0     0
  12     4     1     1    0.4843       1.4843        0.0          0.0         12.3750      14.1250       0     C     0     0     0     0
  13     5     1     1    0.4843       1.4843        0.0          0.0          2.3750      12.3750       0     C     0     0     0     0
```

```
          ********** SUMMARY  OF  MATERIAL  DATA **********

MATERIAL    MATERIAL      ------------ THERMAL PARAMETERS ------------
 NUMBER       NAME        -- TEMPERATURE-DEPENDENT FUNCTION NUMBERS --
                           CONDUCTIVITY        DENSITY        SPECIFIC HEAT
    1          SSBOX      1.000000D 00     2.860000D-01     1.000000D 00
                              -1                 0               -2
    2            GAS      1.090900D 00     1.000000D 00     1.042000D 00
                              -3                -4                0
    3         HEATER      1.000000D 00     2.840000D-01     1.000000D 00
                              -5                 0               -6
    4          FRAME      1.000000D 00     2.840000D-01     1.000000D 00
                              -5                 0               -6
    5         SPCMNS      1.000000D 00     2.840000D-01     1.000000D 00
                              -5                 0               -6
    6        FTBKGAP      1.090900D 00     1.000000D 00     1.242000D 00
                              -3                -4                0
```

```
********** SUMMARY  OF  INITIAL  TEMPERATURE  DATA **********

NUMBER      INITIAL          POSITION-DEPENDENT FUNCTION NUMBERS
          TEMPERATURE             X OR R       Y OR TH        Z
   1      3.00000D 02               0            0            0
```

```
****************** SUMMARY  OF  HEAT GENERATION  RATE  DATA ******************

NUMBER      POWER            TIME-, TEMPERATURE-, AND POSITION-DEPENDENT NUMBERS
           DENSITY             TIME      TEMPERATURE   X OR R      Y OR TH       Z
   1      1.00000D 00            0            0          -7           0         -8
   2      1.00000D 00            0            0           0           0          1
   3      1.00000D 00            0            0           1           0          0
```

```
                  **********SUMMARY  OF  BOUNDARY  DATA**********

   -------GENERAL------  --TEMPERATURE--    ---------------------------------HEAT TRANSFER COEFFICIENTS-------------------------
                           INFORMATION                                        RELATED FUNCTION NUMBERS

   NO.      TYPE    FCT    TEMPERATURE          FORCED CONV.    RADIATION     NATURAL CONV    EXPONENT      FLUX
                    FLAG   & TIME FCT    ASSOC.
                                         FCTS

    1        1       2     1.000000D 02         1.000000D 00    0.0           0.0             0.0           0.0
                                0        TIME    0              0             0               0             0
                                         TEMP  -11              0             0               0             0

    2        1       2     1.000000D 02         1.000000D 00    0.0           0.0             0.0           0.0
                                0        TIME    0              0             0               0             0
                                         TEMP  -11              0             0               0             0

    3        1       2     1.000000D 02         1.000000D 00    0.0           0.0             0.0           0.0
                                0        TIME    0              0             0               0             0
                                         TEMP  -11              0             0               0             0

    4        1       2     1.000000D 02         1.000000D 00    0.0           0.0             0.0           0.0
                                0        TIME    0              0             0               0             0
                                         TEMP  -11              0             0               0             0

 GROSS LATTICES AND NUMBERS OF INCREMENTS

          R OR X
         0.0          0.212300     0.272300     0.484300     0.984300     1.484300     1.696300     1.756300
         1.968500
               1             4            1            3            3            1            4            1

          Z
         0.0          0.275000     0.625000     2.375000     7.375000    12.375000    14.125000    14.625000
        15.375000
               1             5            1            5            5            1            5            1

                               LISTING  OF  ANALYTIC  FUNCTIONS

    F(V)= A(1)  + A(2)*V + A(3)*V**2 + A(4)*COS(A(5)*V)  + A(6)*EXP(A(7)*V)  + A(8)*SIN(A(9)*V)  + A(10)*LOG(A(11)*V)

 NO.           A(1)       A(2)       A(3)       A(4)       A(5)       A(6)       A(7)       A(8)       A(9)       A(10)      A(11)

          ANALYTIC FUNCTION NO.    1   IS USER SUPPLIED

          ANALYTIC FUNCTION NO.    2   IS USER SUPPLIED
```

```
                LISTING  OF  TABULAR  FUNCTIONS

TABLE NUMBER        1          NUMBER OF PAIRS -        3

      ARGUMENT                       VALUE
   3.20000000D 01                6.45100000D-01
   2.12000000D 02                7.86200000D-01
   9.32000000D 02                1.04800000D 00

TABLE NUMBER        2          NUMBER OF PAIRS -        2

      ARGUMENT                       VALUE
   3.20000000D 01                1.20000000D-01
   7.52000000D 02                1.35000000D-01

TABLE NUMBER        3          NUMBER OF PAIRS -        7

      ARGUMENT                       VALUE
   8.00000000D 01                7.27600000D-03
   1.70000000D 02                8.00000000D-03
   2.60000000D 02                8.66700000D-03
   3.50000000D 02                9.68500000D-03
   4.40000000D 02                1.05040000D-02
   6.20000000D 02                1.20460000D-02
   8.00000000D 02                1.46480000D-02

TABLE NUMBER        4          NUMBER OF PAIRS -        4

      ARGUMENT                       VALUE
   0.0                           6.88700000D-06
   2.00000000D 02                4.79800000D-06
   4.00000000D 02                3.68600000D-06
   6.00000000D 02                2.99200000D-06

TABLE NUMBER        5          NUMBER OF PAIRS -        2

      ARGUMENT                       VALUE
   7.70000000D 01                3.42700000D 00
   1.47200000D 03                1.41100000D 00

TABLE NUMBER        6          NUMBER OF PAIRS -        3

      ARGUMENT                       VALUE
   1.67000000D 02                1.20000000D-01
   3.92000000D 02                1.35000000D-01
   7.52000000D 02                1.50000000D-01
```

```
TABLE NUMBER        7            NUMBER OF PAIRS -        10

      ARGUMENT                         VALUE
   0.0                              1.11517000D 02
   1.59100000D-01                   9.96628000D 01
   3.55900000D-01                   8.78090000D 01
   5.52800000D-01                   7.72720000D 01
   7.49600000D-01                   6.89298000D 01
   9.46500000D-01                   6.19051000D 01
   1.14330000D 00                   5.61975000D 01
   1.34020000D 00                   5.18071000D 01
   1.53700000D 00                   4.82947000D 01
   1.77200000D 00                   4.43433000D 01

TABLE NUMBER        8            NUMBER OF PAIRS -        21

      ARGUMENT                         VALUE
   2.37500000D 00                   1.00000000D 00
   2.85000000D 00                   1.06260000D 00
   3.37500000D 00                   1.12360000D 00
   3.87500000D 00                   1.18160000D 00
   4.37500000D 00                   1.23510000D 00
   4.87500000D 00                   1.28280000D 00
   5.37500000D 00                   1.32360000D 00
   5.87500000D 00                   1.35640000D 00
   6.37500000D 00                   1.38040000D 00
   6.87500000D 00                   1.39510000D 00
   7.37500000D 00                   1.40000000D 00
   7.87500000D 00                   1.39510000D 00
   8.37500000D 00                   1.38040000D 00
   8.87500000D 00                   1.35640000D 00
   9.37500000D 00                   1.32360000D 00
   9.87500000D 00                   1.28280000D 00
   1.03750000D 01                   1.23510000D 00
   1.08750000D 01                   1.18160000D 00
   1.13750000D 01                   1.12360000D 00
   1.18750000D 01                   1.06250000D 00
   1.23750000D 01                   1.00000000D 00

TABLE NUMBER        9            NUMBER OF PAIRS -        2

      ARGUMENT                         VALUE
   0.0                              0.0
   1.00000000D 01                   0.0

TABLE NUMBER       10            NUMBER OF PAIRS -        2

      ARGUMENT                         VALUE
   0.0                              0.0
   1.00000000D 01                   0.0
```

```
TABLE NUMBER        11          NUMBER OF PAIRS -       16

    ARGUMENT                          VALUE
 1.24000000D 02                  7.29200000D-01
 1.29000000D 02                  7.77800000D-01
 1.34000000D 02                  8.33300000D-01
 1.39000000D 02                  8.93100000D-01
 1.44000000D 02                  9.54900000D-01
 1.54000000D 02                  1.09720000D 00
 1.64000000D 02                  1.15760000D 00
 1.74000000D 02                  1.28960000D 00
 1.84000000D 02                  1.38890000D 00
 1.94000000D 02                  1.50490000D 00
 2.04000000D 02                  1.66670000D 00
 2.24000000D 02                  1.73610000D 00
 2.29000000D 02                  1.94440000D 00
 2.39000000D 02                  2.05760000D 00
 2.54000000D 02                  4.86110000D 00
 2.79000000D 02                  3.96826000D 01

TABLE NUMBER        12          NUMBER OF PAIRS -        5

    ARGUMENT                          VALUE
 1.22000000D 02                  2.44000000D-03
 2.12000000D 02                  2.72100000D-03
 3.92000000D 02                  3.18500000D-03
 5.72000000D 02                  3.58800000D-03
 9.32000000D 02                  4.37400000D-03

TABLE NUMBER        13          NUMBER OF PAIRS -        6


    ARGUMENT                          VALUE
 6.25000000D-01                  1.00430000D 02
 4.12499000D 00                  1.00430000D 02
 4.12500000D 00                  7.21200000D 01
 1.06249000D 01                  7.21200000D 01
 1.06250000D 01                  1.00430000D 02
 1.41250000D 01                  1.00430000D 02
```

```
  FINE LATTICE, X OR R, Y OR THETA, AND Z

       1      0.0             2      0.212300         3      0.227300         4      0.242300         5      0.257300
       6      0.272300        7      0.484300         8      0.650967         9      0.817633        10      0.984300
      11      1.150967       12      1.317633        13      1.484300        14      1.696300        15      1.711300
      16      1.726300       17      1.741300        18      1.756300        19      1.968500

       1      0.0             2      0.375000         3      0.425000         4      0.475000         5      0.525000
       6      0.575000        7      0.625000         8      2.375000         9      3.375000        10      4.375000
      11      5.375000       12      6.375000        13      7.375000        14      8.375000        15      9.375000
      16     10.375000       17     11.375000        18     12.375000        19     14.125000        20     14.225000
      21     14.325000       22     14.425000        23     14.525000        24     14.625000        25     15.375000
  THIS PROBLEM CONTAINS  475 NODES.

***** TABLE  8 MUST BE EVALUATED FOR  0.0
      THE VALUE OF THE FUNCTION WILL BE  1.00000000D 00 FOR ALL ARGUMENTS LESS THAN  2.37500000D 00

***** TABLE  7 MUST BE EVALUATED FOR  1.96850000D 00
      THE VALUE OF THE FUNCTION WILL BE  4.43433000D 01 FOR ALL ARGUMENTS GREATER THAN  1.77200000D 00

***** TABLE  8 MUST BE EVALUATED FOR  1.41250000D 01
      THE VALUE OF THE FUNCTION WILL BE  1.00000000D 00 FOR ALL ARGUMENTS GREATER THAN  1.23750000D 01
```

```
HEATING5
ISTMSSB5                                         SURVEILIANCE SPECIMEN SIMULATOR
                                                                                                         IBM 360-***
GROSS GRID                                                        MAP OF THE NODE NUMBERS                09.41.00     11-30-80
                           1         2                                   3         4                             5                             6
                           I         I                                   I         I                             I                             I
   FINE GRID               1         2         3         4         5         6         7         8         9        10        11        12        13
          DISTANCE       0.0      0.21      0.23      0.24      0.26      0.27      0.48      0.65      0.82      0.98      1.15      1.32      1.48
  1    1       0.0         1I--------2---------3---------4---------5---------6---------7---------8---------9--------10--------11--------12--------13---
  2    2      0.38        20I       21I-------22--------23--------24--------25I-------26--------27--------28--------29--------30--------31--------32---
       3      0.43        39I       40I       41        42        43        44I       45        46        47        48        49        50        51
       4      0.48        58I       59I       60        61        62        63I       64        65        66        67        68        69        70
       5      0.53        77I       78I       79        80        81        82I       83        84        85        86        87        88        89
       6      0.58        96I       97I       98        99       100       101I      102       103       104       105       106       107       108
  3    7      0.63       115I      116I      117       118       119       120I-----121I-----122-------123-------124-------125-------126-------127---
  4    8      2.38       134I      135I      136       137       138       139I      140I-----141-------142-------143-------144-------145-------146I
       9      3.38       153I      154I      155       156       157       158I      159I      160       161       162       163       164       165I
      10      4.38       172I      173I      174       175       176       177I      178I      179       180       181       182       183       184I
      11      5.38       191I      192I      193       194       195       196I      197I      198       199       200       201       202       203I
      12      6.38       210I      211I      212       213       214       215I      216I      217       218       219       220       221       222I
  5   13      7.38       229I      230I      231       232       233       234I      235I      236       237       238       239       240       241I
      14      8.38       248I      249I      250       251       252       253I      254I      255       256       257       258       259       260I
      15      9.38       267I      268I      269       270       271       272I      273I      274       275       276       277       278       279I
      16     10.38       286I      287I      288       289       290       291I      292I      293       294       295       296       297       298I
      17     11.38       305I      306I      307       308       309       310I      311I      312       313       314       315       316       317I
  6   18     12.38       324I      325I      326       327       328       329I      330I-----331-------332-------333-------334-------335-------336I
  7   19     14.13       343I      344I      345       346       347       348I-----349I-----350-------351-------352-------353-------354-------355I--
      20     14.23       362I      363I      364       365       366       367I      368       369       370       371       372       373       374
      21     14.33       381I      382I      383       384       385       386I      387       388       389       390       391       392       393
      22     14.43       400I      401I      402       403       404       405I      406       407       408       409       410       411       412
      23     14.53       419I      420I      421       422       423       424I      425       426       427       428       429       430       431
  8   24     14.63       438I      439I-----440-------441-------442-------443I-----444-------445-------446-------447-------448-------449-------450---
  9   25     15.38       457I-----458-------459-------460-------461-------462-------463-------464-------465-------466-------467-------468-------469---
```

```
GROSS GRID            7                                         8          9
                      I                                         I          I
   FINE GRID         14         15         16         17       18         19
        DISTANCE     1.70       1.71       1.73       1.74     1.76       1.97
 1   1      0.0  ---14--------15--------16--------17--------18--------49I
 2   2      0.38 ---33I-------34--------35--------36--------37I        38I
     3      0.43    52I       53         54         55        56I        57I
     4      0.48    71I       72         73         74        75I        76I
     5      0.53    90I       91         92         93        94I        95I
     6      0.58   109I      110        111        112       113I       114I
 3   7      0.63 --128I      129        130        131       132I       133I
 4   8      2.38   147I      148        149        150       151I       152I
     9      3.38   166I      167        168        169       170I       171I
    10      4.38   185I      186        187        188       189I       190I
    11      5.38   204I      205        206        207       208I       209I
    12      6.38   223I      224        225        226       227I       228I
 5  13      7.38   242I      243        244        245       246I       247I
    14      8.38   261I      262        263        264       265I       266I
    15      9.38   280I      281        282        283       284I       285I
    16     10.38   299I      300        301        302       303I       304I
    17     11.38   318I      319        320        321       322I       323I
 6  18     12.38   337I      338        339        340       341I       342I
 7  19     14.13 --356I      357        358        359       360I       361I
    20     14.23   375I      376        377        378       379I       380I
    21     14.33   394I      395        396        397       398I       399I
    22     14.43   413I      414        415        416       417I       418I
    23     14.53   432I      433        434        435       436I       437I
 8  24     14.63 --451I------452-------453-------454-------455I       456I
 9  25     15.38 --470-------471-------472-------473-------474-------475I
```

```
HEATINGS                    SURVEILIANCE SPECIMEN SIMULATOR                                                         IBM 360-***
ISTMSSRS                                                                                                            09.41.43     11-30-80
                         STEADY STATE TEMPERATURE DISTRIBUTION  AFTER   31 ITERATIONS, TIME = 0.0
GROSS GRID            1         2                                         3         4                              5                             6
                      I         I                                         I         I                              I                             I
  FINE GRID           1         2         3         4         5           6         7         8         9         10        11        12        13
       DISTANCE      0.0       0.21      0.23      0.24      0.26        0.27      0.48      0.65      0.82      0.98      1.15      1.32      1.48
 1    1     0.0    140I37---145.96---146.19---146.44---146.61---146.79---147.74---147.44---146.58---145.35---143.09---142.24---140.39
 2    2     0.38   153I89    160I20---160.13---160.08---160.04---160I00---160.00---155.44---158.38---156.96---155.28---153.44---151.52
      3     0.43   156I61    164I09    171.75    179.17    186.21    192I75    224.47    228.68    228.81    227.85    226.30    223.82    217.49
      4     0.48   159I50    168I32    185.15    201.27    216.39    230I25    286.04    293.25    294.16    293.53    292.12    289.31    280.34
      5     0.53   162I49    172I88    202.53    230.54    256.44    279I80    346.68    354.47    355.65    355.26    354.01    351.29    342.08
      6     0.58   165I53    177I70    226.94    272.73    314.70    352I20    407.27    412.92    413.94    413.69    412.63    410.42    403.70
 3    7     0.63   168I52    182I59    260.47    332.56    400.27    464I40---467I50---466.89---469.47---469.34---468.46---466.97---464.07
 4    8     2.38   178I87    195I26    273.63    346.12    413.96    477I97    480I85---482.15---482.60---482.50---481.66---480.22---478I21
      9     3.38   182I07    199I20    279.51    353.71    423.08    488I51    491I47    492.79    493.29    493.06    492.16    490.64    488I54
     10     4.38   184I86    202I69    285.11    361.16    432.19    499I14    502I20    503.53    504.02    503.75    502.78    501.17    498I98
     11     5.38   187I09    205I49    289.75    367.42    439.87    508I15    511I29    512.65    513.13    512.82    511.79    510.11    507I83
     12     6.38   188I52    207I31    292.83    371.60    445.03    514I21    517I40    518.77    519.25    518.92    517.85    516.13    513I79
 5   13     7.38   189I02    207I95    293.95    373.14    446.94    516I47    519I69    521.07    521.54    521.20    520.12    518.38    516I02
     14     8.38   188I57    207I38    293.01    371.88    445.40    514I66    517I86    519.24    519.71    519.38    518.32    516.59    514I25
     15     9.38   187I21    205I65    290.15    368.02    440.65    509I10    512I25    513.61    514.09    513.78    512.76    511.07    508I79
     16    10.38   185I04    202I94    285.74    362.12    433.43    500I65    503I73    505.07    505.57    505.30    504.32    502.71    500I50
     17    11.38   182I35    199I58    280.43    355.10    424.89    490I71    493I70    495.03    495.54    495.31    494.41    492.88    490I76
 6   18    12.38   179I34    195I89    274.98    348.10    416.51    481I03    483I95---485.20---485.04---485.63---484.79---483.34---481I30
 7   19    14.13   171I38    186I08    264.51    337.06    405.13    469I57---472I71---474.16---474.78---474.63---473.76---472.23---470I06
     20    14.23   166I83    178I35    212.26    244.26    273.92    300I84    393.07    410.91    416.40    417.24    415.00    408.16    388.88
     21    14.33   162I57    171I86    187.85    203.28    217.94    231I67    324.78    348.56    356.61    357.96    354.76    344.89    319.13
     22    14.43   158I99    166I97    175.24    183.31    191.12    198I61    267.21    288.22    295.83    296.95    293.46    283.54    260.16
     23    14.53   156I19    163I71    167.61    171.44    175.17    178I78    216.30    229.05    233.64    233.78    230.63    223.19    207.78
 8   24    14.63   154I02    162I49---162.62---163.04---163.45---163I83---167.64---168.78---168.52---167.11---164.70---161.42---157.35
 9   25    15.38   139I66---145.84---146.16---146.46---146.75---147.02---149.39---149.86---149.39---148.15---146.27---143.82---140.86
```

```
GROSS GRID           7                                                 8            9
                     I                                                 I            I
   FINE GRID        14           15           16           17          18           19
         DISTANCE  1.70         1.71         1.73         1.74        1.76         1.97
 1   1      0.0 --137.56---137.30---137.04---136.77---136.49---134I36
 2   2      0.38 --149I33---149.28---149.24---149.23---149I24     143I71
     3      0.43   182I99       176.14       168.77       161.01      153I01       146I43
     4      0.48   221I50       207.11       191.42       174.67      157I19       149I35
     5      0.53   272I34       248.22       221.45       192.47      161I74       152I40
     6      0.58   346I53       307.96       264.75       217.51      166I58       155I50
 3   7      0.63 --464I40       395.61       326.11       251.95      171I52       158I56
 4   8      2.38   [illegible]  409.49       340.06       265.72      185I09       169I85
     9      3.38   485[illegible] 418.18     347.11       270.92      188I17       172I32
    10      4.38   495I[illegible] 426.86    354.03       275.85      190I81       174I39
    11      5.38   504I[illegible] 434.21    359.86       279.98      192I97       176I07
    12      6.38   510I[illegible] 439.15    363.78       282.74      194I39       177I18
 5  13      7.38   512I[illegible] 440.99    365.25       283.77      194I91       177I58
    14      8.38   510I45       439.52       364.0[illegible] 282.94  194I47       177I24
    15      9.38   505I06       434.99       360.47       280.38      193I14       176I20
    16     10.38   496I89       428.11       354.99       276.50      191I08       174I59
    17     11.38   487I28       420.00       348.51       271.87      188I58       172I62
 6  18     12.38   477I94       412.04       342.06       267.10      185I74       170I36
 7  19     14.13 --466I48       400.42       330.52       255.84      174I82       161I30
    20     14.23   293I29       265.52       234.88       201.77      166I61       156I33
    21     14.33   221I95       207.67       192.41       176.34      159I68       151I65
    22     14.43   187I66       179.80       171.59       163.11      154I44       147I69
    23     14.53   166I98       163.13       159.15       155.08      150I93       144I56
 8  24     14.63 --151I10---150.72---150.25---149.78---149I31     142I16
 9  25     15.38 --136.37---136.02---135.66---135.30---134.94---129I31

                          TEMPERATURES ON NUMBERED BOUNDARIES

                        BOUNDARY NUMBER     TEMPERATURE
                               1              100.000000
                               2              100.000000
                               3              100.000000
                               4              100.000000

                     ELAPSED CPU TIME IS   37.15 SECONDS

     THE  MAXIMUM  TEMPERATURE  IS -  5.21539D 02       (+-0.1 PERCENT)

     MAX. TEMP. APPEARS AT NODES   -         236        237        238

     THE  MINIMUM  TEMPERATURE  IS -  1.29311D 02       (+-0.1 PERCENT)

     MIN. TEMP. APPEARS AT NODES   -         475

          THE STEADY STATE CALCULATIONS HAVE BEEN COMPLETED.

          NUMBER OF ITERATIONS COMPLETED =     31
```

As a sample output for the PVWS capsule model, this particular case has the following parameters:

1. computed nuclear heating rate modified by the Z-dependent factor,
2. a front gap thickness of 1.524 mm (0.060 in.),
3. an annular gap thickness of 0.508 mm (0.020 in.),
4. helium sweep gas, and
5. no electric heat applied.

The units used in the computations are Btu, h, in., and °F.

```
HEATING5, A MULTI-DIMENSIONAL HEAT CONDUCTION CODE WITH TEMPERATURE-DEPENDENT THERMAL PROPERTIES,
NON-LINEAR AND SURFACE-TO-SURFACE BOUNDARY CONDITIONS AND CHANGE-OF-PHASE CAPABILITIES.
THIS VERSION OF THE CODE IS DESCRIBED IN ORNL/TM/CSD-15.
THE TRANSIENT SOLUTION CAN BE CALCULATED BY AN IMPLICIT TECHNIQUE (CRANK-NICOLSON OR
BACKWARDS EULER) FOR PROBLEMS WITH MATERIALS WHICH ARE NOT ALLOWED TO UNDERGO A PHASE CHANGE.
THE ONE-DIMENSIONAL R SPHERICAL MODEL WAS ADDED NOV. 75. THIS MODEL MAY BE ACCESSED
BY SPECIFYING NGEOM = 10 IN THE INPUT DATA.
HEATING5 WAS WRITTEN BY

     W.D. TURNER
     D.C. ELROD
     I.I. SIMAN-TOV
     COMPUTER SCIENCES DIVISION
     UNION CARBIDE CORPORATION, NUCLEAR DIVISION
              OAK RIDGE, TENNESSEE 37830

THIS VERSION OF HEATING CAN HANDLE A MAXIMUM OF   1360 LATTICE POINTS.

INPUT RETURN

  DATE 11-30-80
  TIME 09.41.53

  JOB DESCRIPTION-- PVWS  COMPLETE CAPSULE(100%HE,1.0G,,.060 GAP,.020 ANNULUS)
  THE PROBLEM WILL BE TERMINATED AFTER       200 SECONDS
  GEOMETRY TYPE NUMBER     8 (OR XZ  )
  NUMBER OF REGIONS     98
  NUMBER OF MATERIALS      9
  NUMBER OF HEAT GENERATION FUNCTIONS     7
  NUMBER OF INITIAL TEMPERATURE FUNCTIONS      1
  NUMBER OF DIFFERENT KINDS OF BOUNDARIES     3
  THIS PROBLEM INVOLVES TEMPERATURE-DEPENDENT PROPERTIES.
  NUMBER OF POINTS IN GROSS X OR R LATTICE    33
  NUMBER OF POINTS IN GROSS Y OR THETA LATTICE     0
  NUMBER OF POINTS IN GROSS Z LATTICE    39
  NUMBER OF ANALYTIC FUNCTIONS    2
  NUMBER OF TABULAR FUNCTIONS   15
  A DATA SET TO BE USED TO CREATE GRAPHICAL OUTPUT OF
  THE TEMPERATURE DISTRIBUTION WILL BE STORED ON UNIT 31
  THE FINAL TEMPERATURE DISTRIBUTION WILL BE WRITTEN ON UNIT     32 IN FORMATTED FORM
  PROBLEM TYPE NUMBER     1
  STEADY STATE CONVERGENCE CRITERION  1.0000000D-05
  MAXIMUM NUMBER OF STEADY-STATE ITERATIONS   -500
  NUMBER OF ITERATIONS BETWEEN TEMPERATURE DEPENDENT
  PARAMETER EVALUATIONS FOR STEADY STATE CALCULATIONS      0
  INITIAL OVERRELAXATION FACTOR (BETA) FOR STEADY STATE CALCULATIONS  1.90000000
  INITIAL TIME  0.0
```

```
                                                SUMMARY OF REGION DATA
NUMBERS AND FCN NUMBER  ****************************** DIMENSIONS ******************************  -------- BOUNDARY NUMBERS --------
REG.  MATL  INIT  HEAT   LEFT-X-OR   RIGHT-X-OR  LOWER-Y-OR  UPPER-Y-OR       REAR-Z     FRONT-Z   LF-X  RT-X  LO-Y  UP-Y  RR-Z  FT-Z
 NO.   NO.  TEMP  GEN.   INNER-R     OUTER-R     LEFT-THETA  RIGHT-THETA                           IN-R  OT-R  LF-O  RT-O
   1     1     1     1     0.0          8.8500     0.0         0.0            0.0        0.3750      1     2     0     0     1     0
   2     1     1     1     0.0          0.0900     0.0         0.0            0.3750    15.3250      1     0     0     0     0     0
   3     1     1     1     0.0          8.8500     0.0         0.0           15.3250    16.0000      1     2     0     0     0     1
   4     1     1     1     8.4750       8.8500     0.0         0.0            0.3750    15.3250      0     2     0     0     0     0
   5     2     1     0     0.0900       8.4750     0.0         0.0            0.3750     1.1250      0     0     0     0     0     0
   6     3     1     0     0.0900       0.1500     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
   7     2     1     0     0.0900       8.4750     0.0         0.0           14.6250    15.3250      0     0     0     0     0     0
   8     2     1     0     7.7250       8.4750     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
   9     4     1     1     0.1500       0.3100     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  10     4     1     1     1.3100       1.5220     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  11     4     1     1     1.8720       2.0840     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  12     4     1     1     3.0840       3.2960     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  13     4     1     1     3.8960       4.1080     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  14     4     1     1     5.1080       5.3200     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  15     5     1     1     0.3100       1.3100     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  16     5     1     1     2.0840       3.0840     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  17     5     1     1     4.1080       5.1080     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  18     4     1     1     1.5220       1.6077     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  19     4     1     1     1.7864       1.8720     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  20     4     1     1     3.2960       3.5067     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  21     4     1     1     3.6854       3.8960     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  22     4     1     1     5.3200       5.5307     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  23     4     1     1     5.7094       5.9200     0.0         0.0            1.1250    14.6250      0     0     0     0     0     0
  24     4     1     1     1.6077       1.7864     0.0         0.0            1.1250     2.4621      0     0     0     0     0     0
  25     4     1     1     1.6077       1.7864     0.0         0.0            2.7882     3.9621      0     0     0     0     0     0
  26     4     1     1     1.6077       1.7864     0.0         0.0            4.2882     5.4621      0     0     0     0     0     0
  27     4     1     1     1.6077       1.7864     0.0         0.0            5.7882     6.9621      0     0     0     0     0     0
  28     4     1     1     1.6077       1.7864     0.0         0.0            7.2882     8.4621      0     0     0     0     0     0
  29     4     1     1     1.6077       1.7864     0.0         0.0            8.7882     9.9621      0     0     0     0     0     0
  30     4     1     1     1.6077       1.7864     0.0         0.0           10.2882    11.4621      0     0     0     0     0     0
  31     4     1     1     1.6077       1.7864     0.0         0.0           11.7882    12.9621      0     0     0     0     0     0
  32     4     1     1     1.6077       1.7864     0.0         0.0           13.2882    14.6250      0     0     0     0     0     0
  33     4     1     1     3.5067       3.6854     0.0         0.0            1.1250     2.4621      0     0     0     0     0     0
  34     4     1     1     3.5067       3.6854     0.0         0.0            2.7882     3.9621      0     0     0     0     0     0
  35     4     1     1     3.5067       3.6854     0.0         0.0            4.2882     5.4621      0     0     0     0     0     0
  36     4     1     1     3.5067       3.6654     0.0         0.0            5.7882     6.9621      0     0     0     0     0     0
  37     4     1     1     3.5067       3.6854     0.0         0.0            7.2882     8.4621      0     0     0     0     0     0
  38     4     1     1     3.5067       3.6854     0.0         0.0            8.7882     9.9621      0     0     0     0     0     0
  39     4     1     1     3.5067       3.6854     0.0         0.0           10.2882    11.4621      0     0     0     0     0     0
  40     4     1     1     3.5067       3.6854     0.0         0.0           11.7882    12.9621      0     0     0     0     0     0
  41     4     1     1     3.5067       3.6854     0.0         0.0           13.2882    14.6250      0     0     0     0     0     0
  42     4     1     1     5.5307       5.7094     0.0         0.0            1.1250     2.4621      0     0     0     0     0     0
  43     4     1     1     5.5307       5.7094     0.0         0.0            2.7882     3.9621      0     0     0     0     0     0
  44     4     1     1     5.5307       5.7094     0.0         0.0            4.2882     5.4621      0     0     0     0     0     0
  45     4     1     1     5.5307       5.7094     0.0         0.0            5.7882     6.9621      0     0     0     0     0     0
  46     4     1     1     5.5307       5.7094     0.0         0.0            7.2882     8.4621      0     0     0     0     0     0
  47     4     1     1     5.5307       5.7094     0.0         0.0            8.7882     9.9621      0     0     0     0     0     0
  48     4     1     1     5.5307       5.7094     0.0         0.0           10.2882    11.4621      0     0     0     0     0     0
  49     4     1     1     5.5307       5.7094     0.0         0.0           11.7882    12.9621      0     0     0     0     0     0
  50     4     1     1     5.5307       5.7094     0.0         0.0           13.2882    14.6250      0     0     0     0     0     0
  51     6     1     0     1.6077       1.6277     0.0         0.0            2.4621     2.7881      0     3     0     0     0     0
  52     6     1     0     1.6077       1.6277     0.0         0.0            3.9621     4.2881      0     3     0     0     0     0
  53     6     1     0     1.6077       1.6277     0.0         0.0            5.4621     5.7881      0     3     0     0     0     0
  54     6     1     0     1.6077       1.6277     0.0         0.0            6.9621     7.2881      0     3     0     0     0     0
  55     6     1     0     1.6077       1.6277     0.0         0.0            8.4621     8.7881      0     3     0     0     0     0
  56     6     1     0     1.6077       1.6277     0.0         0.0            9.9621    10.2881      0     3     0     0     0     0
  57     6     1     0     1.6077       1.6277     0.0         0.0           11.4621    11.7881      0     3     0     0     0     0
  58     6     1     0     1.6077       1.6277     0.0         0.0           12.9621    13.2881      0     3     0     0     0     0
```

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59   6   1   0   1.7664   1.7864   0.0   0.0    2.4621    2.7881   3   0   0   0   0   0
60   6   1   0   1.7664   1.7864   0.0   0.0    3.9621    4.2881   3   0   0   0   0   0
61   6   1   0   1.7664   1.7864   0.0   0.0    5.4621    5.7881   3   0   0   0   0   0
62   6   1   0   1.7664   1.7864   0.0   0.0    6.9621    7.2881   3   0   0   0   0   0
63   6   1   0   1.7664   1.7864   0.0   0.0    8.4621    8.7881   3   0   0   0   0   0
64   6   1   0   1.7664   1.7864   0.0   0.0    9.9621   10.2881   3   0   0   0   0   0
65   6   1   0   1.7664   1.7864   0.0   0.0   11.4621   11.7881   3   0   0   0   0   0
66   6   1   0   1.7664   1.7864   0.0   0.0   12.9621   13.2881   3   0   0   0   0   0
67   7   1   0   3.5067   3.5267   0.0   0.0    2.4621    2.7881   0   3   0   0   0   0
68   7   1   0   3.5067   3.5267   0.0   0.0    3.9621    4.2881   0   3   0   0   0   0
69   7   1   0   3.5067   3.5267   0.0   0.0    5.4621    5.7881   0   3   0   0   0   0
70   7   1   0   3.5067   3.5267   0.0   0.0    6.9621    7.2881   0   3   0   0   0   0
71   7   1   0   3.5067   3.5267   0.0   0.0    8.4621    8.7881   0   3   0   0   0   0
72   7   1   0   3.5067   3.5267   0.0   0.0    9.9621   10.2881   0   3   0   0   0   0
73   7   1   0   3.5067   3.5267   0.0   0.0   11.4621   11.7881   0   3   0   0   0   0
74   7   1   0   3.5067   3.5267   0.0   0.0   12.9621   13.2881   0   3   0   0   0   0
75   7   1   0   3.6654   3.6854   0.0   0.0    2.4621    2.7881   3   0   0   0   0   0
76   7   1   0   3.6654   3.6854   0.0   0.0    3.9621    4.2881   3   0   0   0   0   0
77   7   1   0   3.6654   3.6854   0.0   0.0    5.4621    5.7881   3   0   0   0   0   0
78   7   1   0   3.6654   3.6854   0.0   0.0    6.9621    7.2881   3   0   0   0   0   0
79   7   1   0   3.6654   3.6854   0.0   0.0    8.4621    8.7881   3   0   0   0   0   0
80   7   1   0   3.6654   3.6854   0.0   0.0    9.9621   10.2881   3   0   0   0   0   0
81   7   1   0   3.6654   3.6854   0.0   0.0   11.4621   11.7881   3   0   0   0   0   0
82   7   1   0   3.6654   3.6854   0.0   0.0   12.9621   13.2881   3   0   0   0   0   0
83   8   1   0   5.5307   5.5507   0.0   0.0    2.4621    2.7881   0   3   0   0   0   0
84   8   1   0   5.5307   5.5507   0.0   0.0    3.9621    4.2881   0   3   0   0   0   0
85   8   1   0   5.5307   5.5507   0.0   0.0    5.4621    5.7881   0   3   0   0   0   0
86   8   1   0   5.5307   5.5507   0.0   0.0    6.9621    7.2881   0   3   0   0   0   0
87   8   1   0   5.5307   5.5507   0.0   0.0    8.4621    8.7881   0   3   0   0   0   0
88   8   1   0   5.5307   5.5507   0.0   0.0    9.9621   10.2881   0   3   0   0   0   0
89   8   1   0   5.5307   5.5507   0.0   0.0   11.4621   11.7881   0   3   0   0   0   0
90   8   1   0   5.5307   5.5507   0.0   0.0   12.9621   13.2881   0   3   0   0   0   0
91   8   1   0   5.6894   5.7094   0.0   0.0    2.4621    2.7881   3   0   0   0   0   0
92   8   1   0   5.6894   5.7094   0.0   0.0    3.9621    4.2881   3   0   0   0   0   0
93   8   1   0   5.6894   5.7094   0.0   0.0    5.4621    5.7881   3   0   0   0   0   0
94   8   1   0   5.6894   5.7094   0.0   0.0    6.9621    7.2881   3   0   0   0   0   0
95   8   1   0   5.6894   5.7094   0.0   0.0    8.4621    8.7881   3   0   0   0   0   0
96   8   1   0   5.6894   5.7094   0.0   0.0    9.9621   10.2881   3   0   0   0   0   0
97   8   1   0   5.6894   5.7094   0.0   0.0   11.4621   11.7881   3   0   0   0   0   0
98   8   1   0   5.6894   5.7094   0.0   0.0   12.9621   13.2881   3   0   0   0   0   0
```

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          *********** SUMMARY  OF  MATERIAL  DATA ***********

MATERIAL   MATERIAL     ------------- THERMAL PARAMETERS ------------
 NUMBER      NAME       -- TEMPERATURE-DEPENDENT FUNCTION NUMBERS --
                        CONDUCTIVITY       DENSITY       SPECIFIC HEAT
    1        SSBOX      1.000000D 00    2.860000D-01    1.000000D 00
                             -1               0               -2
    2       GASGAP      1.000000D 00    1.000000D 00    1.242000D 00
                             -3              -4                0
    3      FRNTGAS      1.000000D 00    1.000000D 00    1.242000D 00
                             -3              -4                0
    4       CSTEEL      1.000000D 00    2.840000D-01    1.000000D 00
                             -5               0               -6
    5       SPECMN      5.000000D-01    2.840000D-01    1.000000D 00
                             -5               0               -6
    6      GASANL1      1.000000D 00    1.000000D 00    1.242000D 00
                             -3              -4                0
    7      GASANL2      1.000000D 00    1.000000D 00    1.242000D 00
                             -3              -4                0
    8      GASANL3      1.000000D 00    1.000000D 00    1.242000D 00
                             -3              -4                0
    9       SSTEEL      1.000000D 00    2.860000D-01    1.000000D 00
                             -1               0               -2

*********** SUMMARY  OF  INITIAL  TEMPERATURE  DATA ***********

NUMBER     INITIAL         POSITION-DEPENDENT FUNCTION NUMBERS
         TEMPERATURE          X OR R      Y OR TH        Z
   1     3.00000D 02            0            0           0

******************* SUMMARY  OF  HEAT GENERATION  RATE  DATA *******************

NUMBER      POWER            TIME-, TEMPERATURE-, AND POSITION-DEPENDENT NUMBERS
           DENSITY             TIME     TEMPERATURE  X OR R      Y OR TH       Z
   1     1.00000D 00            0            0         -7           0         -8
   2     5.00000D-01            0            0          0           0          1
   3     5.00000D-01            0            0          0           0          1
   4     1.50000D 00            0            0          0           0          1
   5     1.50000D 00            0            0          0           0          1
   6     3.50000D 00            0            0          0           0          1
   7     3.50000D 00            0            0          0           0          1
```

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                          **********SUMMARY  OF  BOUNDARY  DATA**********

 -------GENERAL------  --TEMPERATURE--   ----------------------------------HEAT TRANSFER COEFFICIENTS---------------------------
                         INFORMATION                                       RELATED FUNCTION NUMBERS

 NO.     TYPE    FCT    TEMPERATURE                 FORCED CONV.    RADIATION      NATURAL CONV    EXPONENT       FLUX
                 FLAG   & TIME FCT      ASSOC.
                                        FCTS

  1       1       2     1.04000D 02                1.00000D 00     0.0            0.0             0.C            0.0
                             0          TIME        0              0              0               0              0
                                        TEMP      -11              0              0               0              0

  2       1       2     1.00000D 02                1.00000D 00     0.0            0.0             0.C            0.0
                             0          TIME        0              0              0               0              0
                                        TEMP      -11              0              0               0              0

  3       1       0     1.00000D 02                4.40000D 00     0.0            0.0             0.0            0.0
                             0

GROSS LATTICES AND NUMBERS OF INCREMENTS

           R OR X
           0.0         0.090000     0.150000     0.310000     0.810000     1.310000     1.522000     1.607700
           1.627700    1.766400     1.786400     1.872000     2.084000     2.584000     3.084000     3.296000
           3.506700    3.526700     3.665400     3.685400     3.896000     4.108000     4.608000     5.108000
           5.320000    5.530700     5.550700     5.689400     5.709400     5.920000     7.725000     8.475000
           8.850000
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1            1            1

           Z
           0.0         0.375000     1.125000     2.462050     2.462100     2.788100     2.788150     3.962050
           3.962100    4.288100     4.288150     5.462050     5.462100     5.788100     5.788150     6.962050
           6.962100    7.288100     7.288150     7.875000     8.462050     8.462100     8.788100     8.788150
           9.962050    9.962100    10.288100    10.288150    11.462050    11.462100    11.788100    11.788150
          12.962050   12.962100    13.288100    13.288150    14.625000    15.325000    16.000000
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1            1            1
                  1           1            1            1            1            1

                                LISTING  OF  ANALYTIC  FUNCTIONS

   F(V)= A(1)  + A(2)*V  + A(3)*V**2 + A(4)*COS(A(5)*V)  + A(6)*EXP(A(7)*V)  + A(8)*SIN(A(9)*V)  + A(10)*LOG(A(11)*V)

NO.          A(1)        A(2)        A(3)        A(4)        A(5)        A(6)        A(7)        A(8)        A(9)        A(10)       A(11)

         ANALYTIC FUNCTION NO.     1   IS USER SUPPLIED

         ANALYTIC FUNCTION NO.     2   IS USER SUPPLIED
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                 LISTING  OF  TABULAR  FUNCTIONS

TABLE NUMBER        1          NUMBER OF PAIRS -        3

     ARGUMENT                        VALUE
   3.20000000D 01                6.45100000D-01
   2.12000000D 02                7.66200000D-01
   9.32000000D 02                1.04800000D 00

TABLE NUMBER        2          NUMBER OF PAIRS -        2

     ARGUMENT                        VALUE
   3.20000000D 01                1.20000000D-01
   7.52000000D 02                1.35000000D-01

TABLE NUMBER        3          NUMBER OF PAIRS -        7

     ARGUMENT                        VALUE
   8.00000000D 01                7.27600000D-03
   1.70000000D 02                8.00000000D-03
   2.60000000D 02                8.86700000D-03
   3.50000000D 02                9.68500000D-03
   4.40000000D 02                1.05040000D-02
   6.20000000D 02                1.20460000D-02
   8.00000000D 02                1.46480000D-02

TABLE NUMBER        4          NUMBER OF PAIRS -        4

     ARGUMENT                        VALUE
   0.0                           6.88700000D-06
   2.00000000D 02                4.79800000D-06
   4.00000000D 02                3.68600000D-06
   6.00000000D 02                2.99200000D-06

TABLE NUMBER        5          NUMBER OF PAIRS -        2

     ARGUMENT                        VALUE
   7.70000000D 01                3.42700000D 00
   1.47200000D 03                1.41100000D 00

TABLE NUMBER        6          NUMBER OF PAIRS -        3

     ARGUMENT                        VALUE
   1.67000000D 02                1.20000000D-01
   3.92000000D 02                1.35000000D-01
   7.52000000D 02                1.50000000D-01

TABLE NUMBER        7          NUMBER OF PAIRS -       25

     ARGUMENT                        VALUE
   0.0                           2.54645000D 01
   1.20100000D-01                2.32693000D 01
   3.20100000D-01                2.01960000D 01
   5.20100000D-01                1.75617000D 01
   7.09800000D-01                1.53665000D 01
   9.09800000D-01                1.31713000D 01
   1.10980000D 00                1.14151000D 01
   1.30000000D 00                1.00980000D 01
   1.50000000D 00                8.78090000D 00
   1.70000000D 00                7.46370000D 00
   2.49020000D 00                4.39040000D 00
   2.98000000D 00                3.07330000D 00
   3.77010000D 00                 2.19520000D 00
   4.55000000D 00                 1.49270000D 00
   5.34020000D 00                 1.27320000D 00
   5.72950000D 00                 1.27320000D 00
   6.22950000D 00                 1.44880000D 00
   6.62010000D 00                 1.71230000D 00
   7.00980000D 00                 2.10740000D 00
   7.40980000D 00                 2.80990000D 00
   7.80000000D 00                 3.77580000D 00
   8.19020000D 00                 5.09290000D 00
   8.39020000D 00                 5.52710000D 00
   8.58000000D 00                 6.62960000D 00
   8.75980000D 00                 7.55150000D 00

TABLE NUMBER        8          NUMBER OF PAIRS -        21

     ARGUMENT                       VALUE
   2.37500000D 00                 1.00000000D 00
   2.85000000D 00                 1.06260000D 00
   3.37500000D 00                 1.12360000D 00
   3.87500000D 00                 1.18160000D 00
   4.37500000D 00                 1.23510000D 00
   4.87500000D 00                 1.28280000D 00
   5.37500000D 00                 1.32360000D 00
   5.87500000D 00                 1.35640000D 00
   6.37500000D 00                 1.38040000D 00
   6.87500000D 00                 1.39510000D 00
   7.37500000D 00                 1.40000000D 00
   7.87500000D 00                 1.39510000D 00
   8.37500000D 00                 1.38040000D 00
   8.87500000D 00                 1.35640000D 00
   9.37500000D 00                 1.32360000D 00
   9.87500000D 00                 1.28280000D 00
   1.03750000D 01                 1.23510000D 00
   1.08750000D 01                 1.18160000D 00
   1.13750000D 01                 1.12360000D 00
   1.18750000D 01                 1.06250000D 00
   1.23750000D 01                 1.00000000D 00

TABLE NUMBER        9          NUMBER OF PAIRS -         2

     ARGUMENT                       VALUE
  0.0                             0.0
   1.00000000D 01                 0.0

TABLE NUMBER       10          NUMBER OF PAIRS -         2

     ARGUMENT                       VALUE
  0.0                             0.0
   1.00000000D 01                 0.0

TABLE NUMBER       11          NUMBER OF PAIRS -        16

     ARGUMENT                       VALUE
   1.24000000D 02                 7.29200000D-01
   1.29000000D 02                 7.77800000D-01
   1.34000000D 02                 8.33300000D-01
   1.39000000D 02                 8.93100000D-01
   1.44000000D 02                 9.54900000D-01
   1.54000000D 02                 1.09720000D 00
   1.64000000D 02                 1.15760000D 00
   1.74000000D 02                 1.28960000D 00
   1.84000000D 02                 1.38890000D 00
   1.94000000D 02                 1.50490000D 00
   2.04000000D 02                 1.66670000D 00
   2.24000000D 02                 1.73610000D 00
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    2.29000000D 02                 1.94440000D 00
    2.39000000D 02                 2.05760000D 00
    2.54000000D 02                 4.86110000D 00
    2.79000000D 02                 3.96826000D 01

TABLE NUMBER       12           NUMBER OF PAIRS -        5

      ARGUMENT                       VALUE
    1.22000000D 02                 2.44000000D-03
    2.12000000D 02                 2.72100000D-03
    3.92000000D 02                 3.18500000D-03
    5.72000000D 02                 3.58800000D-03
    9.32000000D 02                 4.37400000D-03

TABLE NUMBER       13           NUMBER OF PAIRS -        6

      ARGUMENT                       VALUE
    1.12500000D 00                 1.10890000D 02
    4.62490000D 00                 1.10890000D 02
    4.62500000D 00                 1.19420000D 02
    1.11249000D 01                 1.19420000D 02
    1.11250000D 01                 1.10890000D 02
    1.35000000D 01                 1.10890000D 02

TABLE NUMBER       14           NUMBER OF PAIRS -        6

      ARGUMENT                       VALUE
    1.12500000D 00                 9.01300000D 01
    4.62490000D 00                 9.01300000D 01
    4.62500000D 00                 8.36900000D 01
    1.11249000D 01                 8.36900000D 01
    1.11250000D 01                 9.01300000D 01
    1.35000000D 01                 9.01300000D 01

TABLE NUMBER       15           NUMBER OF PAIRS -       25

      ARGUMENT                       VALUE
    0.0                            3.24453000D 01
    1.19700000D-01                 2.93281000D 01
    3.16500000D-01                 2.53767000D 01
    5.13400000D-01                 2.19522000D 01
    7.10200000D-01                 1.87910000D 01
    9.07100000D-01                 1.60690000D 01
    1.10390000D 00                 1.37420000D 01
    1.30080000D 00                 1.17663000D 01
    1.49760000D 00                 1.00541000D 01
    2.58030000D 00                 5.40200000D 00
    3.76140000D 00                 1.88790000D 00
    4.15510000D 00                 1.44880000D 00
    4.54880000D 00                 1.14150000D 00
    4.94250000D 00                 9.22000000D-01
    5.33620000D 00                 7.46400000D-01
    5.92680000D 00                 5.70800000D-01
    6.41890000D 00                 4.39000000D-01
    6.61570000D 00                 4.39000000D-01
    7.00940000D 00                 3.95100000D-01
    7.20630000D 00                 3.51200000D-01
    7.79680000D 00                 3.51200000D-01
    7.99370000D 00                 3.95100000D-01
    8.38740000D 00                 4.39000000D-01
    8.58420000D 00                 4.39000000D-01
    8.75590000D 00                 5.26900000D-01
```

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FINE LATTICE, X OR R, Y OR THETA, AND Z

      1      0.0               2      0.090000        3      0.150000        4      0.310000        5      0.810000
      6      1.310000          7      1.522000        8      1.607700        9      1.627700       10      1.766400
     11      1.786400         12      1.872000       13      2.084000       14      2.584000       15      3.084000
     16      3.296000         17      3.506700       18      3.526700       19      3.665400       20      3.685400
     21      3.896000         22      4.108000       23      4.608000       24      5.108000       25      5.320000
     26      5.530700         27      5.550700       28      5.689400       29      5.709400       30      5.920000
     31      7.725000         32      8.475000       33      8.850000

      1      0.0               2      0.375000        3      1.125000        4      2.462050        5      2.462100
      6      2.788100          7      2.788150        8      3.962050        9      3.962100       10      4.288100
     11      4.288150         12      5.462050       13      5.462100       14      5.788100       15      5.788150
     16      6.962050         17      6.962100       18      7.288100       19      7.288150       20      7.875000
     21      8.462050         22      8.462100       23      8.788100       24      8.788150       25      9.962050
     26      9.962100         27     10.288100       28     10.288150       29     11.462050       30     11.462100
     31     11.788100         32     11.788150       33     12.962050       34     12.962100       35     13.288100
     36     13.288150         37     14.625000       38     15.325000       39     16.000000

    THIS PROBLEM CONTAINS 1287 NODES.

***** TABLE  8 MUST BE EVALUATED FOR  0.0
      THE VALUE OF THE FUNCTION WILL BE  1.00000000D 00 FOR ALL ARGUMENTS LESS THAN  2.37500000D 00

***** TABLE  7 MUST BE EVALUATED FOR  8.85000000D 00
      THE VALUE OF THE FUNCTION WILL BE  7.55150000D 00 FOR ALL ARGUMENTS GREATER THAN  8.75980000D 00

***** TABLE  8 MUST BE EVALUATED FOR  1.29620500D 01
      THE VALUE OF THE FUNCTION WILL BE  1.00000000D 00 FOR ALL ARGUMENTS GREATER THAN  1.23750000D 01
```

```
HEATINGS                                  PVWS  COMPLETE CAPSULE(100%HE,1.0G,,.060 GAP,.020 ANNULUS)
ISTMSA11                                                                                      IBM 360-***
                                                      MAP OF THE NODE NUMBERS                 09.42.02     11-30-80
GROSS GRID              1       2       3       4       5       6       7       8       9      10      11      12      13
                        I       I       I       I       I       I       I       I       I       I       I       I       I
    FINE GRID           1       2       3       4       5       6       7       8       9      10      11      12      13
          DISTANCE    0.0    0.09    0.15    0.31    0.81    1.31    1.52    1.61    1.63    1.77    1.79    1.87    2.08
  1   1        0.0      1I------2-------3-------4-------5-------6-------7-------8-------9------10------11------12------13---
  2   2       0.38     34I     35I-----36------37------38------39------40------41------42------43------44------45------46---
  3   3       1.13     67I     68I-----69I-----70I-----71------72I-----73------74------75------76------77------78------79---
  4   4       2.46    100I    101I    102I    103I    104     105I    106     107I----108-----109-----110I    111     112I
  5   5       2.46    133I    134I    135I    136I    137     138I    139     140I----141I    142I----143I    144     145I
  6   6       2.79    166I    167I    168I    169I    170     171I    172     173I----174I    175I----176I    177     178I
  7   7       2.79    199I    200I    201I    202I    203     204I    205     206I----207-----208-----209I    210     211I
  8   8       3.96    232I    233I    234I    235I    236     237I    238     239I----240-----241-----242I    243     244I
  9   9       3.96    265I    266I    267I    268I    269     270I    271     272I----273I    274I----275I    276     277I
 10  10       4.29    298I    299I    300I    301I    302     303I    304     305I----306I    307I----308I    309     310I
 11  11       4.29    331I    332I    333I    334I    335     336I    337     338I----339-----340-----341I    342     343I
 12  12       5.46    364I    365I    366I    367I    368     369I    370     371I----372-----373-----374I    375     376I
 13  13       5.46    397I    398I    399I    400I    401     402I    403     404I----405I    406I----407I    408     409I
 14  14       5.79    430I    431I    432I    433I    434     435I    436     437I----438I    439I----440I    441     442I
 15  15       5.79    463I    464I    465I    466I    467     468I    469     470I----471-----472-----473I    474     475I
 16  16       6.96    496I    497I    498I    499I    500     501I    502     503I----504-----505-----506I    507     508I
 17  17       6.96    529I    530I    531I    532I    533     534I    535     536I----537I    538I----539I    540     541I
 18  18       7.29    562I    563I    564I    565I    566     567I    568     569I----570I    571I----572I    573     574I
 19  19       7.29    595I    596I    597I    598I    599     600I    601     602I----603-----604-----605I    606     607I
 20  20       7.88    628I    629I    630I    631I    632     633I    634     635     636     637     638     639     640I
 21  21       8.46    661I    662I    663I    664I    665     666I    667     668I----669-----670-----671I    672     673I
 22  22       8.46    694I    695I    696I    697I    698     699I    700     701I----702I    703I----704I    705     706I
 23  23       8.79    727I    728I    729I    730I    731     732I    733     734I----735I    736I----737I    738     739I
 24  24       8.79    760I    761I    762I    763I    764     765I    766     767I----768-----769-----770I    771     772I
 25  25       9.96    793I    794I    795I    796I    797     798I    799     800I----801-----802-----803I    804     805I
 26  26       9.96    826I    827I    828I    829I    830     831I    832     833I----834I    835I----836I    837     838I
 27  27      10.29    859I    860I    861I    862I    863     864I    865     866I----867I    868I----869I    870     871I
 28  28      10.29    892I    893I    894I    895I    896     897I    898     899I----900-----901-----902I    903     904I
 29  29      11.46    925I    926I    927I    928I    929     930I    931     932I----933-----934-----935I    936     937I
 30  30      11.46    958I    959I    960I    961I    962     963I    964     965I----966I    967I----968I    969     970I
 31  31      11.79    991I    992I    993I    994I    995     996I    997     998I----999I   1000I---1001I   1002    1003I
 32  32      11.79   1024I   1025I   1026I   1027I   1028    1029I   1030    1031I---1032----1033----1034I   1035    1036I
 33  33      12.96   1057I   1058I   1059I   1060I   1061    1062I   1063    1064I---1065----1066----1067I   1068    1069I
 34  34      12.96   1090I   1091I   1092I   1093I   1094    1095I   1096    1097I---1098I   1099I---1100I   1101    1102I
 35  35      13.29   1123I   1124I   1125I   1126I   1127    1128I   1129    1130I---1131I   1132I---1133I   1134    1135I
 36  36      13.29   1156I   1157I   1158I   1159I   1160    1161I   1162    1163I---1164----1165----1166I   1167    1168I
 37  37      14.63   1189I   1190I---1191I---1192I---1193----1194I---1195----1196----1197----1198----1199----1200----1201I--
 38  38      15.33   1222I   1223I---1224----1225----1226----1227----1228----1229----1230----1231----1232----1233----1234---
 39  39      16.00   1255I---1256----1257----1258----1259----1260----1261----1262----1263----1264----1265----1266----1267---
```

100

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GROSS GRID              14         15         16         17         18         19         20         21         22         23         24         25         26
                         I          I          I          I          I          I          I          I          I          I          I          I          I
    FINE GRID           14         15         16         17         18         19         20         21         22         23         24         25         26
          DISTANCE     2.58       3.08       3.30       3.51       3.53       3.67       3.69       3.90       4.11       4.61       5.11       5.32       5.53
 1    1       0.0  ---14--------15--------16--------17--------18--------19--------20--------21--------22--------23--------24--------25--------26---
 2    2       0.38 ---47--------48--------49--------50--------51--------52--------53--------54--------55--------56--------57--------58--------59---
 3    3       1.13 ---80--------81I-------82--------83--------84--------85--------86--------87--------88I-------89--------90I-------91--------92---
 4    4       2.46    113       114I       115       116I-----117------118------119I       120       121I       122       123I       124       125---
 5    5       2.46    146       147I       148       149I-----150I      151I-----152I       153       154I       155       156I       157       158I--
 6    6       2.79    179       180I       181       182I-----183I      184I-----185I       186       187I       188       189I       190       191I--
 7    7       2.79    212       213I       214       215I-----216------217------218I       219       220I       221       222I       223       224I--
 8    8       3.96    245       246I       247       248I-----249------250------251I       252       253I       254       255I       256       257---
 9    9       3.96    278       279I       280       281I-----282I      283I-----284I       285       286I       287       288I       289       290I--
10   10       4.29    311       312I       313       314I-----315I      316I-----317I       318       319I       320       321I       322       323I--
11   11       4.29    344       345I       346       347I-----348------349------350I       351       352I       353       354I       355       356I--
12   12       5.46    377       378I       379       380I-----381------382------383I       384       385I       386       387I       388       389---
13   13       5.46    410       411I       412       413I-----414I      415I-----416I       417       418I       419       420I       421       422I--
14   14       5.79    443       444I       445       446I-----447I      448I-----449I       450       451I       452       453I       454       455I--
15   15       5.79    476       477I       478       479I-----480------481------482I       483       484I       485       486I       487       488I--
16   16       6.96    509       510I       511       512I-----513------514------515I       516       517I       518       519I       520       521---
17   17       6.96    542       543I       544       545I-----546I      547I-----548I       549       550I       551       552I       553       554I--
18   18       7.29    575       576I       577       578I-----579I      580I-----581I       582       583I       584       585I       586       587I--
19   19       7.29    608       609I       610       611I-----612------613------614I       615       616I       617       618I       619       620I--
20   20       7.88    641       642I       643       644        645        646        647        648       649I       650       651I       652       653
21   21       8.46    674       675I       676       677I-----678------679------680I       681       682I       683       684I       685       686---
22   22       8.46    707       708I       709       710I-----711I      712I-----713I       714       715I       716       717I       718       719I--
23   23       8.79    740       741I       742       743I-----744I      745I-----746I       747       748I       749       750I       751       752I--
24   24       8.79    773       774I       775       776I-----777------778------779I       780       781I       782       783I       784       785I--
25   25       9.96    806       807I       808       809I-----810------811------812I       813       814I       815       816I       817       818---
26   26       9.96    839       840I       841       842I-----843I      844I-----845I       846       847I       848       849I       850       851I--
27   27      10.29    872       873I       874       875I-----876I      877I-----878I       879       880I       881       882I       883       884I--
28   28      10.29    905       906I       907       908I-----909------910------911I       912       913I       914       915I       916       917I--
29   29      11.46    938       939I       940       941I-----942------943------944I       945       946I       947       948I       949       950---
30   30      11.46    971       972I       973       974I-----975I      976I-----977I       978       979I       980       981I       982       983I--
31   31      11.79   1004      1005I      1006      1007I----1008I     1009I----1010I      1011      1012I      1013      1014I      1015      1016I--
32   32      11.79   1037      1038I      1039      1040I----1041-----1042-----1043I      1044      1045I      1046      1047I      1048      1049I--
33   33      12.96   1070      1071I      1072      1073I----1074-----1075-----1076I      1077      1078I      1079      1080I      1081      1082---
34   34      12.96   1103      1104I      1105      1106I----1107I     1108I----1109I      1110      1111I      1112      1113I      1114      1115I--
35   35      13.29   1136      1137I      1138      1139I----1140I     1141I----1142I      1143      1144I      1145      1146I      1147      1148I--
36   36      13.29   1169      1170I      1171      1172I----1173-----1174-----1175I      1176      1177I      1178      1179I      1180      1181I--
37   37      14.63 -1202------1203I-----1204------1205------1206------1207------1208------1209------1210I-----1211------1212I-----1213------1214---
38   38      15.33 -1235------1236------1237------1238------1239------1240------1241------1242------1243------1244------1245------1246------1247---
39   39      16.00 -1268------1269------1270------1271------1272------1273------1274------1275------1276------1277------1278------1279------1280---
```

```
GROSS GRID               27        28        29        30        31        32        33
                          I         I         I         I         I         I         I
   FINE GRID             27        28        29        30        31        32        33
        DISTANCE       5.55      5.69      5.71      5.92      7.73      8.48      8.85
 1   1        0.0 -------27--------28--------29--------30--------31--------32--------33I
 2   2       0.38 -------60--------61--------62--------63--------64--------65I       66I
 3   3       1.13 -------93--------94--------95--------96I-------97I       98I       99I
 4   4       2.46 ------126-------127-------128I      129I      130I      131I      132I
 5   5       2.46 ------159I      160I------161I      162I      163I      164I      165I
 6   6       2.79 ------192I      193I------194I      195I      196I      197I      198I
 7   7       2.79 ------225-------226-------227I      228I      229I      230I      231I
 8   8       3.96 ------258-------259-------260I      261I      262I      263I      264I
 9   9       3.96 ------291I      292I------293I      294I      295I      296I      297I
10  10       4.29 ------324I      325I------326I      327I      328I      329I      330I
11  11       4.29 ------357-------358-------359I      360I      361I      362I      363I
12  12       5.46 ------390-------391-------392I      393I      394I      395I      396I
13  13       5.46 ------423I      424I------425I      426I      427I      428I      429I
14  14       5.79 ------456I      457I------458I      459I      460I      461I      462I
15  15       5.79 ------489-------490-------491I      492I      493I      494I      495I
16  16       6.96 ------522-------523-------524I      525I      526I      527I      528I
17  17       6.96 ------555I      556I------557I      558I      559I      560I      561I
18  18       7.29 ------588I      589I------590I      591I      592I      593I      594I
19  19       7.29 ------621-------622-------623I      624I      625I      626I      627I
20  20       7.88       654       655       656       657I      658I      659I      660I
21  21       8.46 ------687-------688-------689I      690I      691I      692I      693I
22  22       8.46 ------720I      721I------722I      723I      724I      725I      726I
23  23       8.79 ------753I      754I------755I      756I      757I      758I      759I
24  24       8.79 ------786-------787-------788I      789I      790I      791I      792I
25  25       9.96 ------819-------820-------821I      822I      823I      824I      825I
26  26       9.96 ------852I      853I------854I      855I      856I      857I      858I
27  27      10.29 ------885I      886I------887I      888I      889I      890I      891I
28  28      10.29 ------918-------919-------920I      921I      922I      923I      924I
29  29      11.46 ------951-------952-------953I      954I      955I      956I      957I
30  30      11.46 ------984I      985I------986I      987I      988I      989I      990I
31  31      11.79 -----1017I     1018I-----1019I     1020I     1021I     1022I     1023I
32  32      11.79 -----1050------1051------1052I     1053I     1054I     1055I     1056I
33  33      12.96 -----1083------1084------1085I     1086I     1087I     1088I     1089I
34  34      12.96 -----1116I     1117I-----1118I     1119I     1120I     1121I     1122I
35  35      13.29 -----1149I     1150I-----1151I     1152I     1153I     1154I     1155I
36  36      13.29 -----1182------1183------1184I     1185I     1186I     1187I     1188I
37  37      14.63 -----1215------1216------1217------1218I-----1219I     1220I     1221I
38  38      15.33 -----1248------1249------1250------1251------1252------1253I     1254I
39  39      16.00 -----1281------1282------1283------1284------1285------1286------1287I
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HEATING5                              PVHS  CCMPLETE CAPSULE(100%HE,1.0G,,.060 GAP,.020 ANNULUS)                              IBM 360-***
ISTMSA11                                                                                                                        09.42.48     11-30-80
                                          STEADY STATE TEMPERATURE DISTRIBUTION  AFTER    5 ITERATIONS, TIME = 0.0
GROSS GRID                 1         2          3          4          5          6          7          8          9         10         11         12         13
                           I         I          I          I          I          I          I          I          I          I          I          I          I
   FINE GRID               1         2          3          4          5          6          7          8          9         10         11         12         13
           DISTANCE       0.0       0.09       0.15       0.31       0.81       1.31       1.52       1.61       1.63       1.77       1.79       1.87       2.08
  1   1       0.0      109I80---110.27---110.53---111.01---110.90---109.92---109.47---109.28---109.24---108.95---108.91---108.74---108.33
  2   2       0.38     110I75    111I48---111.61---112.30---112.30---111.26---110.72---110.51---110.46---110.11---110.06---109.86---109.37
  3   3       1.13     117I66    118I84---182I27---182I00---183.75---182I52---182.08---181.88---181.84---181.50---181.45---181.24---180.70
  4   4       2.46     118I61    119I80    184I12    184I44    184.38    182I02    181.25    180I90---180.84---180.36---180I28    180.16    179I77
  5   5       2.46     118I61    119I80    184I12    184I44    184.38    182I02    181.25    180I90---106I58    106I53---180I28    180.16    179I77
  6   6       2.79     118I79    120I00    184I53    184I84    184.65    182I06    181.24    180I86---106I57    106I52---180I20    180.08    179I70
  7   7       2.79     118I79    120I00    184I53    184I84    184.65    182I06    181.24    180I86---180.79---180.28---180I20    180.08    179I70
  8   8       3.96     119I39    120I63    186I08    186I39    185.92    182I83    181.89    181I46---181.30---180.79---180I71    180.56    180I12
  9   9       3.96     119I39    120I63    186I08    186I39    185.92    182I83    181.89    181I46---106I63    106I56---180I70    180.56    180I12
 10  10       4.29     119I54    120I79    186I50    186I82    186.29    183I11    182.16    181I73---106I65    106I58---180I95    180.79    180I32
 11  11       4.29     119I54    120I79    186I50    186I82    186.29    183I11    182.16    181I73---181.65---181.04---180I95    180.79    180I32
 12  12       5.46     120I02    121I30    187I91    188I22    187.54    184I04    183.00    182I54---182.45---181.79---181I69    181.52    181I00
 13  13       5.46     120I02    121I30    187I91    188I22    187.54    184I04    183.00    182I54---106I72    106I65---181I69    181.52    181I00
 14  14       5.79     120I12    121I40    188I20    188I51    187.80    184I26    183.21    182I75---106I74    106I66---181I89    181.70    181I16
 15  15       5.79     120I12    121I40    188I20    188I51    187.80    184I26    183.21    182I75---182.66---181.99---181I89    181.70    181I16
 16  16       6.96     120I33    121I63    188I82    189I13    188.35    184I64    183.55    183I07---182.90---182.28---182I17    181.98    181I43
 17  17       6.96     120I33    121I63    188I82    189I13    188.35    184I64    183.55    183I07---106I76    106I69---182I17    181.98    181I43
 18  18       7.29     120I34    121I64    188I84    189I16    188.39    184I67    183.52    182I99---106I75    106I67---181I97    181.86    181I41
 19  19       7.29     120I34    121I64    188I84    189I16    188.39    184I67    183.52    182I99---182.80---182.10---181I97    181.86    181I41
 20  20       7.88     120I31    121I61    188I72    189I04    188.33    184I88    183.96    183.58    183.50    182.92    182.84    182.51    181I77
 21  21       8.46     120I20    121I49    188I31    188I62    187.87    184I22    183.10    182I58---182.48---181.71---181I58    181.47    181I01
 22  22       8.46     120I20    121I49    188I31    188I62    187.87    184I22    183.10    182I58---106I72    106I64---181I58    181.47    181I01
 23  23       8.79     120I11    121I40    187I99    188I30    187.56    183I93    182.86    182I30---106I70    106I63---181I49    181.31    180I79
 24  24       8.79     120I11    121I40    187I99    188I30    187.56    183I93    182.86    182I30---182.20---181.60---181I50    181.31    180I79
 25  25       9.96     119I65    120I91    186I43    186I74    186.11    182I76    181.77    181I33---181.25---180.61---180I51    180.33    179I82
 26  26       9.96     119I65    120I91    186I43    186I74    186.11    182I76    181.77    181I33---106I61    106I55---180I51    180.33    179I82
 27  27      10.29     119I50    120I74    185I94    186I25    185.65    182I36    181.36    180I92---106I58    106I54---180I12    179.96    179I48
 28  28      10.29     119I50    120I74    185I94    186I25    185.65    182I36    181.36    180I92---180.83---180.24---180I12    179.96    179I48
 29  29      11.46     118I88    120I08    184I06    184I37    183.94    181I01    180.12    179I73---179.65---179.09---179I00    178.86    178I42
 30  30      11.46     118I88    120I08    184I06    184I37    183.94    181I01    180.12    179I73---106I48    106I42---179I00    178.86    178I42
 31  31      11.79     118I72    119I92    183I62    183I92    183.54    180I69    179.81    179I44---106I45    106I39---178I70    178.58    178I18
 32  32      11.79     118I72    119I92    183I62    183I92    183.54    180I69    179.81    179I44---179.33---178.79---178I71    178.58    178I18
 33  33      12.96     118I33    119I51    182I40    182I71    182.54    180I08    179.29    178I93---178.86---178.37---178I30    178.19    177I84
 34  34      12.96     118I33    119I51    182I40    182I71    182.54    180I08    179.29    178I92---106I41    106I36---178I30    178.19    177I84
 35  35      13.29     118I26    119I43    182I12    182I43    182.39    180I10    179.37    179I03---106I42    106I37---178I43    178.32    177I95
 36  36      13.29     118I26    119I43    182I12    182I43    182.39    180I10    179.37    179I03---178.97---178.54---178I43    178.32    177I95
 37  37      14.63     117I62    118I75---180I63---181I13---181.99---180I74---180.30---180.11---180.06---179.73---179.69---179.40---178I95
 38  38      15.33     113I41    114I11---114.80---116.16---117.15---116.08---115.42---115.14---115.07---114.59---114.52---114.23---113.49
 39  39      16.00     111I78---112.42---112.78---113.49---113.79---112.82---112.28---112.05---112.00---111.63---111.57---111.35---110.70
```

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GROSS GRID          14        15        16        17        18        19        20        21        22        23        24        25        26
                     I         I         I         I         I         I         I         I         I         I         I         I         I
    FINE GRID       14        15        16        17        18        19        20        21        22        23        24        25        26
         DISTANCE  2.50      3.08      3.30      3.51      3.53      3.67      3.69      3.90      4.11      4.61      5.11      5.32      5.53
 1  1      0.0 --107.46---106.02---106.64---106.43---106.42---106.31---106.30---106.16---106.04---105.84---105.67---105.63---105.61
 2  2      0.38 --108.34---107.56---107.34---107.09---107.07---106.95---106.93---106.76---106.62---106.34---106.17---106.12---106.09
 3  3      1.13 --177.06---174I77---174.42---173.51---173.46---173.09---173.04---172.52---172I06---170.05---168I25---167.93---167.67
 4  4      2.46   177.14    173I79    173.00    172I16---172.10---171.64---171I57    171.26    170I92    169.06    166I97    166.49    166.00
 5  5      2.46   177.14    173I79    173.00    172I16---105I84    105I79---171I56    171.26    170I92    169.06    166I97    166.49    166I00
 6  6      2.79   177.05    173I61    172.78    171I09---105I82    105I77---171I27    171.01    170I69    168.84    166I67    166.15    165I50
 7  7      2.79   177.05    173I61    172.78    171I09---171.02---171.34---171I27    171.01    170I69    168.84    166I67    166.15    165I50
 8  8      3.96   177.19    173I46    172.58    171I65---171.57---171.05---170I97    170.67    170I31    168.34    166I04    165.51    164.95
 9  9      3.96   177.19    173I46    172.58    171I65---105I80    105I74---170I97    170.67    170I31    168.34    166I04    165.51    164I95
10 10      4.29   177.29    173I47    172.57    171I63---105I80    105I74---170I94    170.63    170I26    168.26    165I92    165.38    164I80
11 11      4.29   177.29    173I47    172.57    171I63---171.55---171.02---170I94    170.63    170I26    168.26    165I92    165.38    164I84
12 12      5.46   177.74    173I67    172.72    171I73---171.65---171.09---171I00    170.65    170I26    168.15    165I73    165.17    164.60
13 13      5.46   177.74    173I67    172.72    171I73---105I80    105I74---171I00    170.65    170I26    168.15    165I73    165.17    164I59
14 14      5.79   177.84    173I72    172.76    171I76---105I81    105I75---171I02    170.66    170I26    168.13    165I68    165.12    164I54
15 15      5.79   177.84    173I72    172.76    171I76---171.60---171.10---171I02    170.66    170I26    168.13    165I68    165.12    164I54
16 16      6.96   178.03    173I78    172.79    171I76---171.60---171.09---171I00    170.63    170I23    168.06    165I57    164.99    164.39
17 17      6.96   178.03    173I78    172.79    171I76---105I81    105I74---171I00    170.63    170I23    168.06    165I57    164.99    164I39
18 18      7.29   178.05    173I79    172.77    171I66---105I80    105I73---170I81    170.57    170I21    168.06    165I56    164.96    164I20
19 19      7.29   178.05    173I79    172.77    171I66---171.57---170.91---170I81    170.57    170I21    168.06    165I56    164.96    164I20
20 20      7.88   178.10    173I91    173.00    172.14    172.07    171.57    171.51    170.91    170I39    168.10    165I72    165.24    164.85
21 21      8.46   177.69    173I48    172.48    171I40---171.31---170.65---170I55    170.30    169I95    167.81    165I34    164.74    164.08
22 22      8.46   177.69    173I48    172.48    171I39---105I78    105I71---170I55    170.30    169I95    167.81    165I34    164.74    164I08
23 23      8.79   177.47    173I30    172.32    171I30---105I77    105I71---170I55    170.20    169I81    167.68    165I21    164.64    164I04
24 24      8.79   177.47    173I30    172.32    171I30---171.22---170.64---170I55    170.20    169I81    167.68    165I21    164.64    164I04
25 25      9.96   176.64    172I69    171.77    170I81---170.73---170.10---170I10    169.75    169I37    167.30    164I92    164.38    163.84
26 26      9.96   176.64    172I69    171.77    170I81---105I73    105I67---170I10    169.75    169I37    167.30    164I92    164.38    163I84
27 27     10.29   176.40    172I51    171.60    170I64---105I71    105I66---169I94    169.62    169I25    167.21    164I86    164.32    163I75
28 28     10.29   176.40    172I51    171.60    170I64---170.56---170.02---169I94    169.62    169I25    167.21    164I86    164.32    163I75
29 29     11.46   175.59    171I99    171.14    170I24---170.47---169.66---169I59    169.29    168I95    167.03    164I79    164.27    163.74
30 30     11.46   175.59    171I99    171.14    170I24---105I68    105I63---169I59    169.29    168I95    167.03    164I79    164.27    163I74
31 31     11.79   175.44    171I92    171.08    170I19---105I68    105I62---169I55    169.27    168I94    167.06    164I85    164.34    163I79
32 32     11.79   175.44    171I92    171.08    170I19---170.12---169.63---169I55    169.27    168I94    167.06    164I85    164.34    163I79
33 33     12.96   175.32    172I03    171.24    170I30---170.31---169.05---169I79    169.54    169I23    167.46    165I36    164.86    164.34
34 34     12.96   175.32    172I03    171.24    170I30---105I69    105I64---169I78    169.54    169I23    167.46    165I36    164.86    164I34
35 35     13.29   175.43    172I21    171.45    170I64---105I71    105I67---170I07    169.78    169I45    167.67    165I65    165.18    164I70
36 36     13.29   175.43    172I21    171.45    170I64---170.50---170.14---170I07    169.78    169I46    167.67    165I65    165.18    164I70
37 37     14.63 --176.19---173I19---172.56---171.97---171.92---171.56---171.51---171.04---170I56---168.62---166I87---166.56---166.34
38 38     15.33 --111.02---110.46---109.90---109.56---109.53---109.20---109.24---108.91---108.61---108.05---107.69---107.58---107.50
39 39     16.00 --109.53---108.51---108.16---107.05---107.03---107.65---107.62---107.37---107.15---106.75---106.49---106.41---106.36
```

```
GROSS GRID              27         28         29         30         31         32         33
                         I          I          I          I          I          I          I
   FINE GRID            27         28         29         30         31         32         33
        DISTANCE      5.55       5.69       5.71       5.92       7.73       8.48       8.85
 1   1     0.0   --105.60---105.59---105.59---105.58---105.66---105.47---104I23
 2   2     0.38  --106.09---106.07---106.07---106.05---105.98---105I24   104I26
 3   3     1.13  --167.65---167.54---167.52---167I42---109I03   104I54   103I84
 4   4     2.46  --165.97---165.78---165I74   165I75   105I12   104I41   103I74
 5   5     2.46  --105I33   105I30---165I74   165I75   105I12   104I41   103I74
 6   6     2.79  --105I29   105I27---165I30   165I33   104I85   104I49   103I81
 7   7     2.79  --165.55---165.33---165I30   165I33   104I85   104I49   103I81
 8   8     3.96  --164.92---164.69---164I66   164I67   105I01   104I96   104I22
 9   9     3.96  --105I24   105I24---164I66   164I67   105I01   104I96   104I22
10  10     4.29  --105I23   105I20---164I50   164I52   105I10   105I09   104I33
11  11     4.29  --164.77---164.54---164I50   164I52   105I10   105I09   104I33
12  12     5.46  --164.56---164.33---164I29   164I30   105I47   105I49   104I67
13  13     5.46  --105I21   105I48---164I29   164I30   105I47   105I49   104I67
14  14     5.79  --105I20   105I48---164I23   164I24   105I54   105I58   104I74
15  15     5.79  --164.50---164.26---164I23   164I24   105I54   105I58   104I74
16  16     6.96  --164.36---164.11---164I07   164I08   105I72   105I76   104I90
17  17     6.96  --105I19   105I46---164I07   164I08   105I72   105I76   104I90
18  18     7.29  --105I18   105I45---163I90   163I98   105I73   105I77   104I91
19  19     7.29  --164.24---163.95---163I90   163I98   105I73   105I77   104I91
20  20     7.88    164.83     164.66     164.64   164I57   105I71   105I75   104I89
21  21     8.46  --164.04---163.76---163I71   163I78   105I64   105I68   104I83
22  22     8.46  --105I17   105I43---163I70   163I78   105I64   105I68   104I83
23  23     8.79  --105I16   105I44---163I72   163I73   105I58   105I62   104I78
24  24     8.79  --164.04---163.76---163I72   163I73   105I58   105I62   104I78
25  25     9.96  --163.70---163.55---163I51   163I52   105I26   105I28   104I49
26  26     9.96  --105I14   105I42---163I51   163I52   105I26   105I28   104I49
27  27    10.29  --105I14   105I44---163I45   163I47   105I15   105I16   104I39
28  28    10.29  --163.72---163.49---163I45   163I47   105I15   105I16   104I39
29  29    11.46  --163.60---163.45---163I42   163I44   104I73   104I68   103I97
30  30    11.46  --105I13   105I44---163I42   163I44   104I73   104I68   103I97
31  31    11.79  --105I14   105I42---163I50   163I52   104I66   104I56   103I87
32  32    11.79  --163.76---163.54---163I50   163I52   104I66   104I56   103I87
33  33    12.96  --164.20---164.07---164I04   164I07   104I72   104I32   103I67
34  34    12.96  --105I18   105I46---164I04   164I07   104I72   104I32   103I67
35  35    13.29  --105I22   105I20---164I45   164I46   105I08   104I33   103I68
36  36    13.29  --164.60---164.49---164I45   164I46   105I08   104I33   103I68
37  37    14.63  --166.29---166.40---166.46---166I06---109I50   104I80   104I05
38  38    15.33  --107.50---107.46---107.45---107.44---107.46---106I13   104I85
39  39    16.00  --106.35---106.33---106.32---106.30---106.64---105.91---104I71

                        TEMPERATURES ON NUMBERED BOUNDARIES

                       BOUNDARY NUMBER     TEMPERATURE
                              1              104.000000
                              2              100.000000
                              3              100.000000

                        ELAPSED CPU TIME IS   52.75 SECONDS

    THE  MAXIMUM  TEMPERATURE  IS -  1.89159D 02       (+-0.1 PERCENT)

    MAX. TEMP. APPEARS AT NODES   -         499        532        565        598        631

    THE  MINIMUM  TEMPERATURE  IS -  1.03665D 02       (+-0.1 PERCENT)

    MIN. TEMP. APPEARS AT NODES   -         132        165       1089       1122       1155
```

The two subroutines HEATGN and CONDTN used in conjunction with the HEATING5 code are described as follows:

Subroutine HEATGN was used to add electric heat to the nuclear heating at each node to yield a composite nuclear and electric volumetric heat generation rate at node N.

```
SUBROUTINE HEATGN(RVALUE,X,Y,Z,TIM,TSN,VALUE,NUMBER,N)
IMPLICIT REAL*8 (A-H,O-Z)
REAL*8 NUCHET
COMMON/INOUT/IN,IO
COMMON/TABULR/ARG(25,25),VAL(25,25),NTBPRS(25),TPDEP(25)
CALL TABLE(-7,VALUE,X,NUCHET,N,NUMBER)
CALL TABLE(-8,VALUE,Z,FACT,N,NUMBER)
NUCHET=NUCHET*FACT
IF(X.LE..315D0) CALL TABLE (-13,VALUE,Z,EHEAT,N,NUMBER)
IF(X.GT.1.0D0) CALL TABLE (-14,VALUE,Z,EHEAT,N,NUMBER)
RVALUE= NUCHET+VALUE*EHEAT
RETURN
END
```

The user-supplied HEATGN subroutine makes the position, time, and temperature of the node available to the user (X,Y,Z, TIM, TSN). The variable RVALUE $\neq$ 1.0 overrides the value to be computed by the HEATING5 code and uses the value RVALUE instead.

These tabular functions are used in this subroutine:

1. Tabular function 7 is the X-dependent computed volumetric nuclear heating rate.
2. Tabular function 8 is the Z-dependent factor of the nuclear heating rate.
3. Tabular function 13 is the Z-dependent electric volumetric heating rate in the front heater of the PVWS that yields a total of 1 kW/plate.
4. Tabular function 14 is the Z-dependent electric volumetric heating rate in the other heater plates of the PVWS (or SSS) capsule that yields a total of 1 kW/plate.

The TABLE subroutine, part of the HEATING5 code, does a linear interpolation between two adjacent values of the argument. The arguments in the TABLE subroutine are

1. the negative of the tabular function number to be used (i.e., -7),
2. an input constant by which the table values are multiplied in normal use (i.e., 1.0 for computed nuclear heating),
3. the argument value to be interpolated (i.e., particular X),
4. the interpolated value (i.e., the X-dependent nuclear heat generation rate),
5. the node number for which this subroutine is called, and
6. an identifier for the particular parameter that this subroutine is called for (i.e., volumetric heat generation rate).

Because this routine is called for the heat generation function associated with the electric heaters, it will use VALUE as the constant associated with the particular function for which it is called. In this manner, the total output of each heater plate can be controlled by the VALUE argument.

Subroutine CONDTN was used to compute a conductivity for a gas mixture of helium and neon that will be between the values of pure helium conductivity and pure neon conductivity.

The arguments in the CONDTN subroutine are similar to those in the HEATGN subroutine. The CNDMIX argument returns the value of the mixed gas conductivity to be used for node N instead of the one that would otherwise have been computed by the code. VALUE is the weight of helium conductivity in the mixture and is input as the constant value for the conductivity of the helium gas. In that way, the conductivity of the mixture can be controlled by this argument.

```
SUBROUTINE CONDTN(CNDMIX,X,Y,Z,TIM,TSN,VALUE,NUMBER,N)
IMPLICIT REAL*8 (A-H,O-Z)
COMMON/INOUT/IN,IO
COMMON/TABULR/ARG(25,25),VAL(25,25),NTBPRS(25),TPDEP(25)
COMMON/THBSBC/NBDTP,NDIR
VALU=1.0D0
CALL TABLE (-3,VALU,TSN,CHE,N,NUMBER)
CALL TABLE (-12,VALU,TSN,CNE,N,NUMBER)
PHE=VALUE
PNE=1.0D0-PHE
CNDMIX=PHE*CHE+PNE*CNE
RETURN
END
```

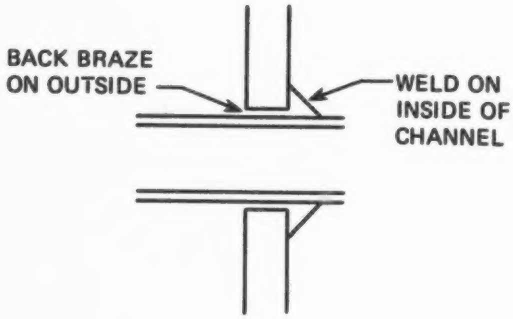
APPENDIX C

AUXILIARY COMPUTATIONS FOR THE HEAT TRANSFER MODEL DEVELOPMENT

Following is a presentation of several of the supporting computations for development of the major models for SSS and PVHS capsules.

C.1 Water Flow Rate Calculation in the Cooler Plates

Each cooler plate consists of eight 4.7625-mm tubes running horizontally parallel to the reactor window and connecting into rectangular inlet and outlet channels on the sides. To preclude a possibility of water leaking into the capsule at the connecting points, the tubes penetrate the channel wall and are welded onto the inside of the channel and brazed on the outside, as shown below.



Assumptions are that this arrangement will probably cause a higher resistance to the flow and may increase the thermal entry length in the tube. To promote more uniform heat transfer along the tube the decision was made to have a high enough water flow rate to operate in the turbulent region.

At Re = 5000, the flow is considered turbulent, and this value was chosen as a starting point to calculate both (1) the necessary total flow rate to be supplied and (2) a heat transfer coefficient from the tube to the water. Because the heat transfer coefficient was satisfactory for this Reynolds number, it was chosen for the design of the cooler plates.

The following computation determines the total water flow rate for the capsule

$$Re = \frac{\rho V D}{\mu} ,$$

or

$$V = \frac{Re\ \nu}{D} ,$$

where

V = the water velocity in the tube,
$\nu = \rho/\mu$ kinematic viscosity of water at 37.8°C is 0.6866×10^{-7} m^2/s,
Re = 5000, and
D = 3.34061 mm for a 3/16-in. tube.

Substituting these values, the water velocity in the tube is computed as

$$V = \frac{5000 \times 0.6866 \times 10^{-5}}{0.0033406} = 1.0276 \text{ m/s} .$$

The total cross-sectional area of 24 tubes is represented by

$$A = \frac{\pi D^2}{4} \times 24 = 6\pi D^2 = 0.2103 \times 10^{-4} \text{ m}^2 .$$

The flow rate is represented by

$$\begin{aligned} VA &= 0.007634 \text{ cfs} \times 21.6171 \times 10^{-6} \text{ m}^3/\text{s}, \\ &= 0.007634 \text{ ft}^3/\text{s} \times 60 \text{ s/min} \times 7.4805 \text{ gal/ft}^3, \\ &= 3.43 \text{ gpm}. \end{aligned}$$

C.2 Radiation Across the Front and Back Gas Gaps in the SSS Capsule

The case presented here is based on the 0.0889-cm gap (as built). Because the heater plate size is 34.29 by 34.90 cm in cross-sectional area, the opposing planes of the container and the heater plate are assumed to be infinite parallel planes with gray-body radiation. In that case, the following correlation is used

$$\dot{q}'''_{rad} = \frac{\sigma(T_1^4 - T_2^4)}{1/\varepsilon_1(T_1) + 1/\varepsilon_2(T_2) - 1} , \qquad (1)$$

where

$\dot{q}'''_{rad}$ = radiation heat flux rate,
ε_1 = emissivity for steel (0.3 at about 213°C),
ε_2 = emissivity for stainless steel (0.75 at about 138°C),
σ = Stefan-Boltzman constant (5.729×10^{-8} W/m^2K^4)
T_1 = computed heater plate surface temperature (487 K), and
T_2 = computed inner surface temperature of the container (371 K).

When substituting these values in Eq. (1), the heat flux rate due to radiation is 576.79 W/m^2.

The heat flow rate due to conduction through the gas gap is

$$\dot{q}''_{con} = \frac{k(T)\Delta T}{d} ,$$

where

$\dot{q}''_{con}$ = conduction heat flow rate,
$k(T)$ = conductivity of helium at $(T_1 + T_2)/2$,
d = gap thickness, and
$\Delta T = T_1 - T_2$.

With k(450 K) = 0.20106 W/m°C, Eq. (1) yields 15303.8 W/m^2.

C.3 Gas Mixture Conductivities

A correlation predicting gas conductivities based on component conductivities is represented as[10]

$$k_m = \frac{y_{he}k_{he}(M_{he})^{1/3} + y_{ne}k_{ne}(M_{ne})^{1/3}}{y_{he}(M_{he})^{1/3} + y_{ne}(M_{ne})^{1/3}} ,$$

where

k_m = conductivity of the mixture,
y = mole fraction of the gas,
k = conductivity,
M = molecular weight of gas,
he = helium, and
ne = neon.

This correlation indicates that the conductivities of the mixture lie between the conductivity of helium and neon.

C.4 Computation of Volumetric Heat Generation Rate in the Heater Plates

The front heater plate in the PVWS capsule is 0.3429 m × 0.349 m × 0.04064 m thick. All other heater plates are 0.3429 m × 0.349 m × 0.0538 m thick. The division of the plate for the model shown in Fig. 13(a) yields

$$(0.1778 \times 0.349 \times 0.04064)m^3 = 2379\ kW/m^3$$

$$(0.1651 \times 0.349 \times 0.04064)m^3 = 1708\ kW/m^3$$

in the front heater plate of the PVWS capsule, and for the other plates:

$$0.6\ \mathrm{kW}/(0.1778 \times 0.349 \times 0.0538)\mathrm{m}^3 = 1796\ \mathrm{kW/m}^3$$

in the top and bottom regions of the plate,

$$0.4\ \mathrm{kW}/(0.1651 \times 0.349 \times 0.0538)\mathrm{m}^3 = 1290\ \mathrm{kW/m}^3$$

in the middle region of the heater plate. Similarly the volumetric heat generation rates for the distribution shown in Fig. 13(b) are

$$0.5\ \mathrm{kW}/0.252 \times 10^{-3}\ \mathrm{m}^3 = 1983\ \mathrm{kW/m}^3$$

for the top and bottom regions of the front heater plate of the PVWS capsule,

$$0.5\ \mathrm{kW}/0.234 \times 10^{-3}\ \mathrm{m}^3 = 2136\ \mathrm{kW/m}^3$$

in the central region of the front heater plate of the PVWS capsule. For the other plates:

$$0.5\ \mathrm{kW}/0.334 \times 10^{-3}\ \mathrm{m}^3 = 1497\ \mathrm{kW/m}^3$$

for the top and bottom regions,

$$0.5\ \mathrm{kW}/0.310 \times 10^{-3}\ \mathrm{m}^3 = 1612\ \mathrm{kW/m}^3$$

in the central region of the heater plates.

C.5 Determination of a Heat Transfer Coefficient in the Cooler Tubes

For better heat transfer, the decision was made to maintain turbulent flow in the cooler tubes, and a Reynolds number of 5000 was chosen. This Reynolds number was then used in the following computation of the heat transfer coefficient based on the Dittus-Boelter correlation for cooling:[11]

$$\mathrm{Nu} = 0.023\ \mathrm{Re}^{0.8}\mathrm{Pr}^{0.3}$$

where

Nu = Nusselt number defined as hD/k,
Pr = Prandtl number defined as $C_p\mu/k$,

C_p = specific heat,
μ = viscosity,
h = heat transfer coefficient,
D = diameter of the tube, and
k = conductivity;

with Re = 5000, Pr = 4.53 for water at 37.8°C, Nu = 32.94, k = 0.6380 W/m°C, and D = 0.0034 m. Substituting in the relation h = Nu·k/D, h = 6181 W/m^2°C.

C.6 Computation of an Effective Conductivity in the Rectangular Model of the Gas Annulus Surrounding the Cooler Tube (Fig. 15)

The heat flow across a cylinder of outer radius R_1 and inner radius R_2 are given by:

$$\dot{q}_c = \frac{2\pi k_g L(T_1 - T_2)}{\ln(R_1/R_2)} ,$$

where

$\dot{q}_c$ = heat flow rate across an annulus,
k_g = conductivity of the gas,
L = length of the cylinder (= 1 unit length in model),
T_1 = temperature at R_1, and
T_2 = temperature at R_2.

The heat flow across a rectangular region is given by:

$$\dot{q}_r = \frac{k_e A_a(T_1 - T_2)}{d} ,$$

where

k_e = effective conductivity of material in this region,
A_a = cross-sectional area, and
d = path length of heat flow.

To maintain the same heat flow and the same temperature drop across the equivalent rectangular gap:

$$\frac{2\pi k_g L}{\ln(R_1/R_2)} = \frac{k_e A_e}{d} .$$

The left-hand side (LHS) term can be multiplied and divided by $R_a = (R_1 + R_2)/2$ and the term $2\pi R_a L$ can be taken as an average cross-sectional heat transfer area in the annulus. The two areas are equated in the PVWS model so that an effective conductivity can be computed in the rectangular gap:

$$k_e = \frac{k_g d}{R_a \ln(R_1 + R_2)} \text{ .}$$

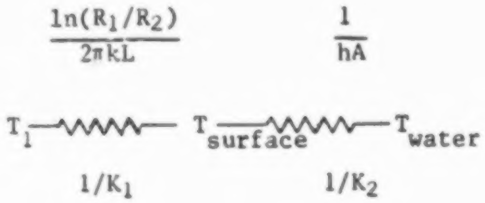
Substituting the values for the geometric terms:

$$k_e = \frac{0.508 \times 10^{-3}}{2.635 \times 10^{-3} \ln(5.779 \times 10^{-3}/4.763 \times 10^{-3})} k_g = 0.997 k_g;$$

this difference in thermal porperties is negligible.

C.7 Determination of an Effective Conductance to Replace the Cooler Tube with a Sole Heat Transfer Coefficient from the Inner Boundary of the Gas into the Water

Because the tube and the conductance into the water are in series as shown in the diagram below:



where

$1/K_e = 1/K_1 + 1/K_2$,
R_1 = tube OD,
R_2 = tube ID,
k = tube material conductivity,
L = tube length (1 unit in model),
h = heat transfer coefficient inside the tube,
K_1 = tube conductance,
K_2 = conductance into the water, and
T = temperature.

The effective conductance of this configuration is

$$K_e = \frac{2\pi k h R_2}{h R_2 \ln(R_1/R_2) + k} \text{ ;}$$

solving for

$$h_e = \frac{K_e}{2R_2}$$

and substituting the values in the model, an effective heat transfer coefficient is obtained:

$$h_e = \frac{15.774 \times 5678.3}{5678.3 \times 0.00167 \times \ln(0.002381/0.00167) + 15.774}$$

$$= 4680 \text{ W/m}^2 {}^\circ\text{C} .$$

The heat transfer coefficient used in the model is 5678.3 $W/m^2 {}^\circ C$.

C.8 Computation of an Effective Heat Transfer Coefficient on the Inner Surface of the Gas Annulus Model

To compensate for the difference in cross-sectional area in the model of the annulus (Fig. 15) and the cross-sectional area of the tube (for heat transfer into the water) an effective heat transfer was calculated.

The heat transfer rate into the water is given by:

$$\dot{q}_s = hA_t(T_s - T_w) ,$$

where

$\dot{q}_s$ = heat transfer rate from the inner surface of the tube,
h = heat transfer coefficient from the inner surface of the tube,
A_t = cross-sectional heat transfer area of the tube,
T_s = inner surface temperature of the tube, and
T_w = bulk water temperature.

The heat transfer rate using the inner surface of the annular gap model is given by:

$$\dot{q}_m = h_m A_m(T_m - T_w) ,$$

where

$\dot{q}_m$ = heat transfer rate from the inner surface of the gap,
h_m = effective heat transfer coefficient for the annular gap model,
A_m = cross-sectional heat transfer area in the model, and
T_m = inner surface temperature in model.

To obtain equivalence between the model and the annular gap behavior:

$$\dot{q}_s = \dot{q}_m \qquad \text{and} \qquad T_s = T_m ,$$

hence

$$h_m = \frac{hA_t}{A_m} ,$$

and substituting the model values

$$h_m = \frac{5.6783 \times 0.2665 \times 10^{-3}}{0.4206 \times 10^{-3}}$$

yields 3.598 kW/m^2 °C.

Appendix D

NUCLEAR HEATING IN THICK IRON SLABS AT THE ORR PSF

The purpose of this work was to determine experimentally and computationally the nuclear heating rates in iron in the PSF of the ORR. This work was performed in support of the NRC-Pressure Vessel Surveillance Program, the objective of which is to verify and upgrade dosimetry and damage correlations for PVs of LWRs.

Reliable computational or experimental nuclear heating rates in thick iron slabs at the ORR PSF were not available. An existing 42/18 group coupled neutron-gamma cross-section working library that includes ^{235}U equilibrium fission product decay gammas[9] was used to predict heating rates in iron for an experiment of heavy section steel technology (HSST) test capsules in the Bulk Shielding Reactor (BSR). The use of this cross-section library resulted in values that were too low.[10] The uncertainties in the nuclear heating rates prompted creation of an expanded cross-section library that includes secondary gammas produced in the iron (due to n, γ reactions). A parametric calculational study with a 1-D cylindrical model (Fig. D.1) was then performed using the discrete ordinate transport code XSDRNPM.[12] For this purpose a third cross-section library was created that does not include either one of the additional gamma sources. The results of using these three libraries on the experimental configuration in the ORR PSF are shown in Fig. D.2. This figure indicates that including the (n, γ) reaction in iron results in much higher nuclear heating rates in the back part of the PVWS capsule. This rise in heating rates occurs because most of the prompt gammas from the reactor are absorbed in the front part of the steel components, thus causing a self-shielding effect. However, the neutrons traveling through the steel produce more gammas that deposit their energy there. These secondary gammas make a substantial contribution to the total heat generation rate in the second half of the PVWS capsule.

Figure D.3 shows results of computationally and experimentally derived heating rates in the HSST test capsules. Using the expanded library resulted in closer agreement between experimental and computational values.

An experiment to determine temperature distributions in a capsule simulating the SSS capsule in the ORR PSF was performed. The experiment consisted of a 60-mm-thick thermal shield located 40 mm from the reactor aluminum window and a capsule 390 × 235 × 50 mm thick (Fig. D.4) with internal dimensions of 216 × 216 × 31 mm and an instrumented steel slab 178 × 178 × 28 mm thick centered in the cavity of the capsule as shown. To force 1-D heat transfer in the direction perpendicular to the reactor window, the slab was surrounded by insulation. The front and back gaps were swept with gas. Two sets of experiments were performed: one with helium and one with neon as the sweep gas. Although the main objective was to obtain a temperature distribution, the results with helium yielded a reliable measure of the average nuclear heating rates in the slab. Table D.1 summarizes the relevant experimental results.

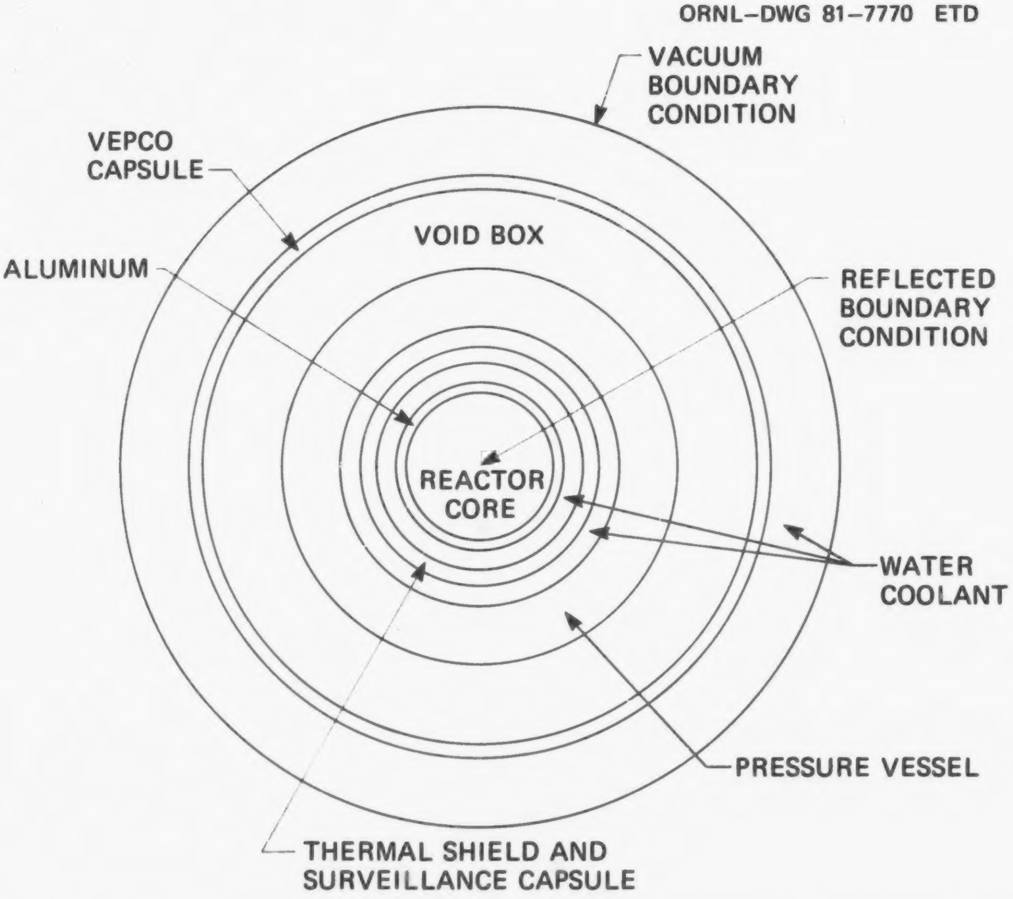

ORNL–DWG 81–7770 ETD
VACUUM BOUNDARY CONDITION
VEPCO CAPSULE
VOID BOX
ALUMINUM
REFLECTED BOUNDARY CONDITION
REACTOR CORE
WATER COOLANT
PRESSURE VESSEL
THERMAL SHIELD AND SURVEILLANCE CAPSULE

Fig. D.1. One-dimensional cylindrical neutron-gamma transport model of SSS and PVWS capsules in ORR PSF.

A 3-D heat transfer computational model of the SSS capsule mock-up was set up. The nuclear heating rate obtained with the expanded cross-section library was used in conjunction with a Y- and Z-dependent factor simulating the flux distribution coming through the ORR window. Both were simulated as explained in connection with the modeling of nuclear heating in the SSS and PVWS capsules. The convection boundary condition on the outer surfaces is the same as used in the basic models presented in Fig. 8. The material properties are given in Table 1 with the exception of the insulation used around the slab. A comparison of experimental and computed temperature distributions for the SSS capsule mock-up experiment are given in Fig. D.5.

In computing an average heating generation rate in the slab by using the computed temperatures corresponding to TE1 and TE11, a value of 0.199 W/g was obtained as compared with the 0.218 W/g derived experimentally. This result indicates that nuclear heating rates can be computed to within

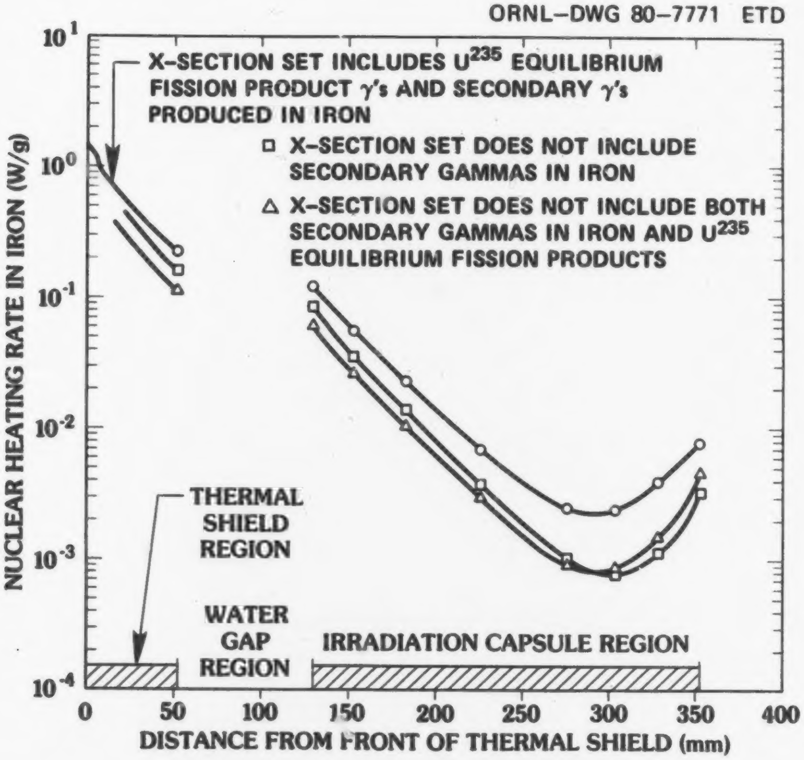


Fig. D.2. Effects of varying cross-section sets on calculated nuclear heating rates in PV wall experiment.

10% of experimentally derived values in thick steel slabs in the ORR PSF when all important gamma sources are taken into account.

Computed nuclear heating rates in the final experimental configuration of the SSS and the PVWS capsules in the ORR PSF are given in Table D.2. This configuration was changed from the one used previously in the parametric study with the various cross-section libraries.

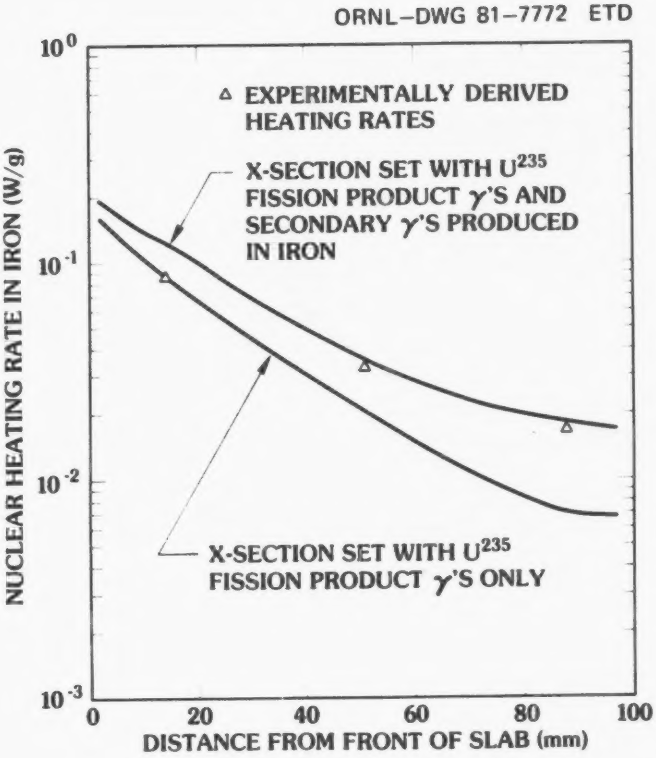


Fig. D.3. Comparison of experimental and computational nuclear heating rates in HSST test capsules.

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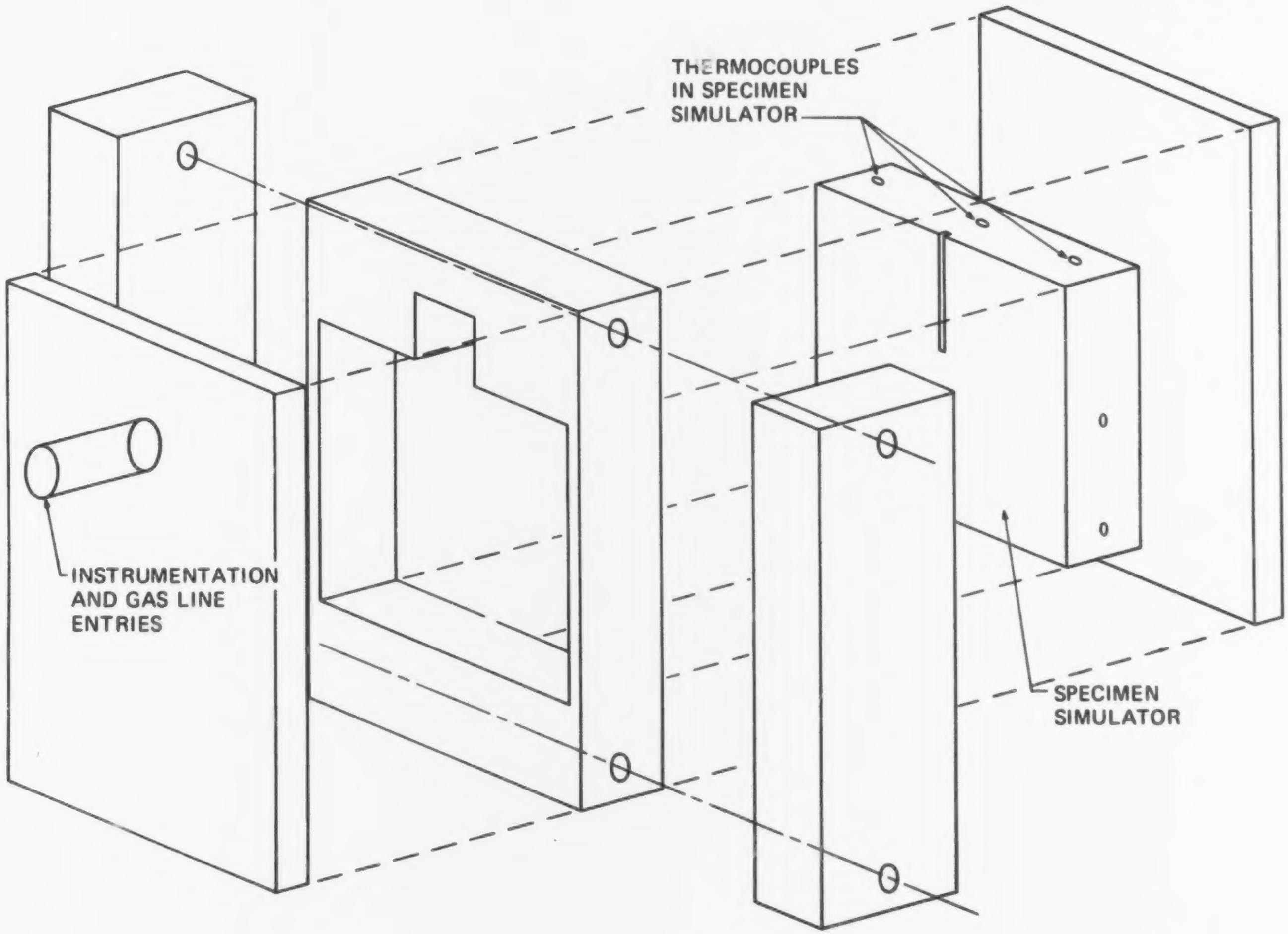
THERMOCOUPLES
IN SPECIMEN
SIMULATOR
INSTRUMENTATION
AND GAS LINE
ENTRIES
SPECIMEN
SIMULATOR

Fig. D.4. SSS mock-up capsule assembly — exploded view.

Table D.1 Experimentally derived nuclear heating rates in iron at the ORR PSF

ORR reactor power level (MW)	Temperatures (°C) measured at:		Total heating rate in instrumented slab (W)	Heating rate per gram iron per MW reactor power[b] (W)
	TE1[a]	TE11		
6	96.1	51.7	307.81	0.0074
12	145.0	61.4	610.16	0.0073
18	189.2	75.3	893.72	0.0072
24	230.8	82.2	1212.80	0.0073
30	268.3	96.1	1497.06	0.0072

[a] See Fig. D.5 for thermocouple locations.

[b] The average heat generation rate is 0.0073 W/g (iron) per MW reactor power with a maximum deviation of >1.5%. Therefore, the heat generation rate at 30-MW reactor power can be considered as 0.218 W/g (iron).

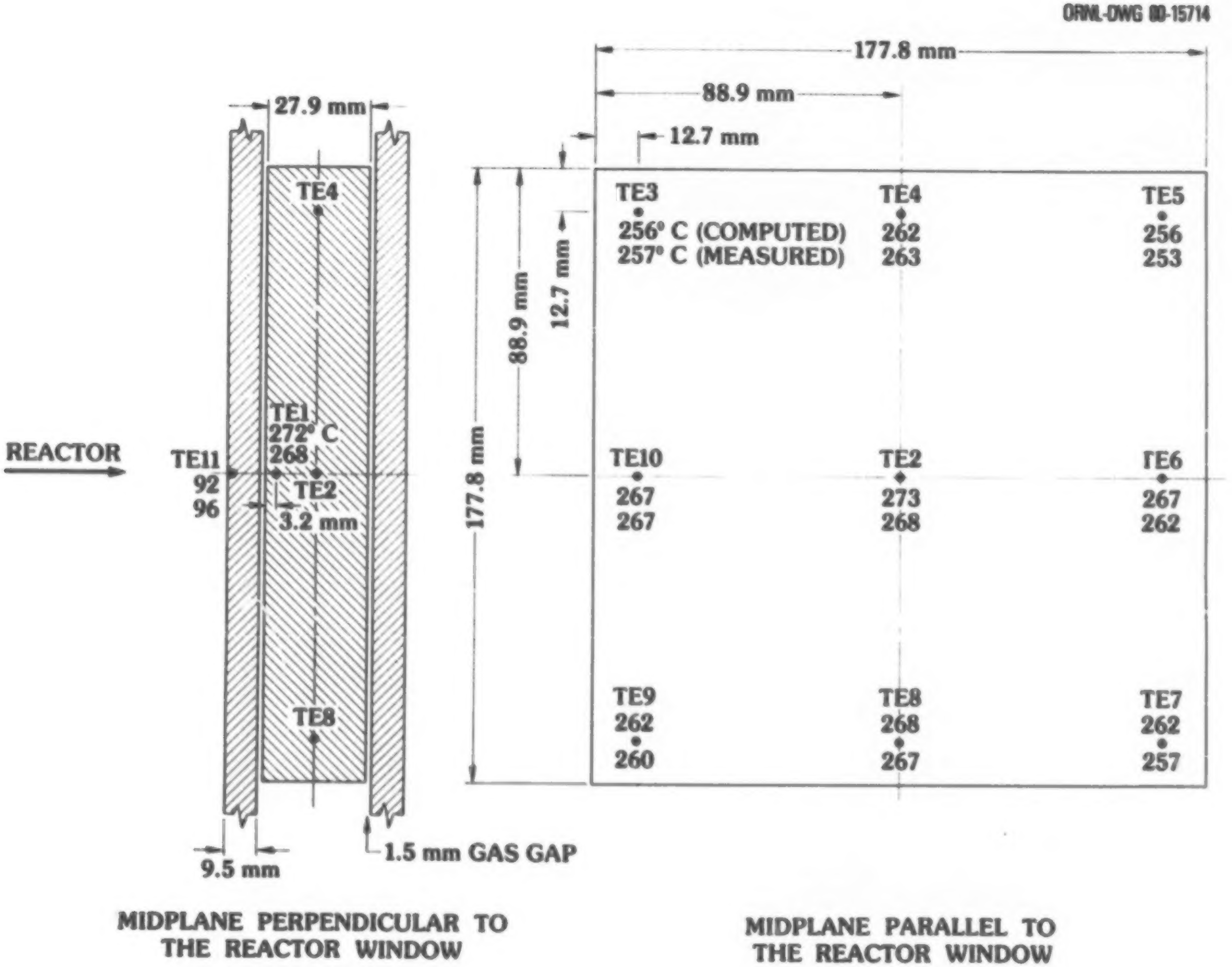
ORNL-DWG 80-15714
27.9 mm
TE4
TE1
272° C
268
REACTOR
TE11
92
96
TE2
3.2 mm
TE8
9.5 mm
1.5 mm GAS GAP
MIDPLANE PERPENDICULAR TO THE REACTOR WINDOW
177.8 mm
88.9 mm
12.7 mm
12.7 mm
88.9 mm
177.8 mm
TE3
256° C (COMPUTED)
257° C (MEASURED)
TE4
262
263
TE5
256
253
TE10
267
267
TE2
273
268
TE6
267
262
TE9
262
260
TE8
268
267
TE7
262
257
MIDPLANE PARALLEL TO THE REACTOR WINDOW

Fig. D.5. Comparison of experimental and computational temperature distribution in SSS mock-up capsule.

Table D.2 Computed nuclear heating rate in the final experimental design configuration

Thermal shield		Surveillance specimen capsule		Instrumented irradiation capsule			
Distance[a] (mm)	Heating rate in iron (W/g)	Distance (mm)	Heating rate in iron (W/g)	Distance[b] (mm)	Heating rate in iron (W/g)	Distance (mm)	Heating rate in iron (W/g)
0.0	1.39	6.054	0.15	0.0	0.058	125.73	0.0031
3.58	1.11	6.858	0.12	03.05	0.058	135.64	0.0029
8.58	0.86	8.11	0.09	08.13	0.046	145.54	0.0029
13.58	0.72	9.202	0.07	13.21	0.040	153.16	0.0031
18.58	0.60			18.03	0.035	158.24	0.0033
23.58	0.50			23.11	0.030	163.07	0.0035
28.58	0.42			28.19	0.026	168.15	0.0039
33.58	0.35			33.02	0.023	172.97	0.0043
38.58	0.03			38.10	0.020	178.05	0.0048
43.58	0.25			43.18	0.017	183.13	0.0055
53.40	0.19			53.09	0.013	188.21	0.0064
60.54	0.15			63.25	0.010	193.04	0.0074
				68.07	0.009	198.12	0.0086
				75.69	0.007	203.20	0.0100
				85.60	0.006	208.03	0.0116
				95.76	0.005	213.11	0.0135
				105.66	0.004	217.93	0.0151
				115.57	0.0034	222.50	0.0172

[a] The distance is given from the front surface of the thermal shield.

[b] The distance is given from the front surface of the PVWS capsule.

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